OPERATING STRATEGIES AND RELATED PERFORMANCE EVALUATIONS FOR A MOVING MERGE CONTROL SYSTEM

By

CHRISTIAN S. BAUER, JR.

A DISSERTATION PRESENTED TO THE GRADUATE COUNCIL OF
THE UNIVERSITY OF FLORIDA
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE
DEGREE OF DOCTOR OF PHILOSOPHY

UNIVERSITY OF FLORIDA

1975

To my Mother, Violet Divine Bauer

May I be led
From darkness to light,
From the unreal to the real,
From death to immortality.

ACKNOWLEDGMENTS

The author wishes to thank the members of his supervisory committee at the University of Florida for their encouragement and support during the preparation of this dissertation, including Professor K. G. Courage, Dr. J. A. Wattleworth, and Dr. J. H. Schaub, of the Department of Civil Engineering, Dr. F. D. Vickers, of the Department of Engineering Technology, and Dr. R. L. Ott, Jr. of the Department of Statistics. Special thanks are extended to Professor Courage, for serving as chairman of the committee, and for supplying many useful insights in the operating behavior and analysis of modern traffic systems.

Several other persons have been of great help to the author and are deserving of individual recognition. Al Thayer, of the Raytheon Corporation, was an excellent reference source on the software used in the early moving merge control experiments leading to this study. Dan Rosen, Sam Tignor, and Justin True, of the Federal Highway Administration in Washington, D. C., provided technical information and background material on the Woburn project. At the University of Florida, Paul Boulay was responsible for coding and testing many of the changes in the on-line control soft-

ware for the Tampa system, and Charles Wallace was responsible for much of the preliminary engineering work for the control system implementation in Tampa; both people were a constant source of innovative ideas for system improvements throughout the project. Bill Holsonback, Traffic Engineer for the City of Tampa, and the members of his technical staff, including Steve Tindale, Scott Shaw, and David Osborne, have been most cooperative during all phases of project work at the field site.

The work described in this dissertation was partially carried out under contract support provided by the Florida Department of Transportation, and the many contributions to the success of the project made by Emmett Owens, State Traffic Operations Engineer, and Gary Price, State Project Coordinator for the Tampa Green Band System are hereby acknowledged.

Finally, the author wishes to thank Dr. G. F. Schrader and Dr. R. D. Kersten, respectively Chairman, Department of Industrial Engineering and Management Systems, and Dean of the College of Engineering at Florida Technological University in Orlando, for providing the author with the leave-of-absence from his faculty position which made this work possible.

TABLE OF CONTENTS

Page

ACKNOWLEDGMENTS.................................... iii

LIST OF TABLES..................................... xi

LIST OF FIGURES.................................... xii

ABSTRACT... xvii

CHAPTER 1 AN OVERVIEW.............................. 1

Introduction............................ 1

Previous Research....................... 7

Research Objectives..................... 21

Research Profile........................ 22

CHAPTER 2 BACKGROUND............................... 25

Prototype Merge Control Systems Tested in Woburn, Massachusetts......... 25

Green Band System Operating Modes....... 29

Woburn Green Band System Operation...... 33

Executive Subroutine.................... 36

Input Service Routine................... 37

Highway Vehicle Processor Program....... 37

Data Logging Subprogram................. 42

Green Band Status Routine: Green Band Generation (Woburn Constant Speed Case)............................ 45

Green Band Status Routine: Determination of An Acceptable Freeway Gap Size for the Green Band Launch Decision.................................. 48

Green Band Update Routine: Green Band Propagation Along Field Display..... 56

Situation Display Subprogram............. 57

Fault Monitor Subprogram................. 58

Green Band Velocity and Volume Program...................................... 58

Woburn Green Band System Mode Transition................................ 60

Results of the Massachusetts Tests....... 65

The Tampa Green Band System Experiment................................. 67

CHAPTER 3 THE TAMPA GREEN BAND SYSTEM................. 72

Introduction............................. 72

The Tampa Ramp........................... 73

Sensor Installation at the Tampa Site..................................... 76

Driver Display Configuration............. 80

Computer Facilities for the Tampa Green Band System........................ 85

Situation Display Board Modifications.... 89

Operator Communication with the On-Line Control Programs in the Tampa Green Band System.................. 91

Hardware Fail-Safe Capabilities of the Tampa Green Band System.............. 92

Tampa Green Band System Mode Change Logic Revisions................... 94

Tampa System Response to Merge Area Congestion........................ 96

Stopped-Gap Mode Band Acceleration Profiles for the Tampa Green Band System................................... 99

Green Band Generation (Tampa Variable Speed Case)...................... 103

Location of the Merge Point for the Tampa System........................ 110

Freeway Detector Placement for the Tampa Green Band System.................. 117

Location of Ramp Detectors and Stop Line................................ 129

CHAPTER 4 ANALYSIS OF TAMPA SYSTEM PERFORMANCE........ 134

Objectives of the Evaluation............ 134

Measurement Techniques: Human Factors Study........................... 140

Measurement Techniques: Public Opinion Study........................... 143

Measurement Techniques: Computer Analysis of Field Sensor Data............ 146

Off-Line Data Analysis.................. 154

Vehicle Identification and Tracking in TOGAP................................ 159

Analysis of Freeway Operations.......... 175

Analysis of Freeway Vehicle Lane Changing Upstream of the Merge Area...... 179

Analysis of Ramp Operations............. 183

Graphical Output of Ramp Vehicle and Green Band Interactions............. 189

Use of Sonic Detectors for Lateral Vehicle Displacement Analysis............ 192

Analysis of Control System Behavior................................. 196

Operational Characteristics of TOGAP Software.......................... 207

CHAPTER 5 DESIGN CONSIDERATIONS FOR FUTURE MERGE CONTROL SYSTEMS....................... 210

Introduction.............................. 210

Errors in the Computation of the Required Freeway Gap Size in the On-Line Control Program.................. 212

Need for Sensor Calibration in the Determination of Freeway Vehicle Lengths................................. 217

Derivation of a Model for Estimating Operational Lengths of Freeway Sensors................................ 223

Development of a Simulation Model for the On-Line Green Band System Control Program......................... 227

Analysis of Simulation Results.......... 256

Initial Processing................... 256

Simulated Green Band Trajectories............................ 259

Case I: Display Transition From "All Green" Status................ 259

Case II: A Displayed Band Edge Moves Backward.................. 278

Case III: A Band Breaks into Smaller Bands......................... 280

Case IV: A Displayed Band Edge Moves Backward.................... 280

Case V: A New Vehicle Enters the Upstream Freeway Section........... 283

Case VI: A Substantial Band Size Reduction.......................... 283

Case VII: A Displayed Band Edge Moves Backward.................... 286

Case VIII: A Displayed Band Edge Moves Backward.................... 286

Case IX: A Displayed Band Jumps to an "All Green" Condition........ 289

Simulation of Woburn GBS Control Logic with Tampa's Variable-Speed Bands........................ 289

System Design Implications of Simulation Results.................... 292

Need for Closed-Loop Control of Display Activity in Merging Control Systems......................... 297

Improved Strategies for System Mode Control.......................... 299

Future Merge Control System Hardware Considerations............... 303

CHAPTER 6 SUMMARY AND CONCLUSIONS.................. 324

Summary of Chapter Coverage........... 324

Conclusions........................... 328

CHAPTER 7 AREAS FOR FUTURE RESEARCH................ 332

APPENDIX A: FORTRAN LISTING OF THE TOGAP DATA ANALYSIS ROUTINES......................... 338

APPENDIX B: FORTRAN LISTING OF THE GREEN BAND ON-LINE CONTROL PROGRAM SIMULATION ROUTINES.................................. 436

LIST OF REFERENCES.. 462

ADDITIONAL REFERENCES... 472

BIOGRAPHICAL SKETCH... 473

LIST OF TABLES

Table: Page

1 Calculations for h_1 and h_2 Components of Required Gap.............................. 54

2 Interrupt Level and Input/Output Channel Assignments for the Woburn and Tampa Green Band System Control Computers........... 88

3 Results of Travel Time Study.................. 122

4 Summary of Evaluation Plan..................... 139

5 Internal Sensor Codes for TOGAP............... 162

6 Illustration of the Numerical Errors in the Equations Used in the Woburn and Tampa Green Band Systems for a Term in the Required Freeway Gap Size Computations.... 214

7 Study Data and Derived Results for Sensor Length Calibration Model...................... 220

8 Tampa Green Band System Control Program Core Map.................................. 305

9 Estimated Cost Breakdown for Packaged Moving Merge Control System Controller........ 321

LIST OF FIGURES

Figure: Page

1 Hierarchy of Freeway Ramp Control System Strategies.............................. 2

2 Illustration of Sequence of Operations in a Gap-Acceptance Merge Control System.............................. 5

3 Schematic Diagram of the Raytheon Corporation Pacer Moving Merge Control System.............................. 28

4 Schematic Diagram of the Raytheon Corporation Green Band Moving Merge Control System.............................. 30

5 Green Band System Control Software Flow Chart.............................. 34

6 Green Band System Control Software Function Diagram.............................. 35

7 Illustration of Scheme Used by Raytheon for the Identification of Double-Loop Sensor Event Times.............................. 38

8 Data Logging Routine Tape Output Format for Woburn Green Band System.................. 44

9 Green Band Display Element Parameter Definitions.............................. 49

10 Possible Mode Transitions in the Woburn Green Band System.............................. 61

11 Woburn Green Band System Mode Decision Space.............................. 62

12 Five-Minute Volumes at Sensor R10 on January 24, 1974.............................. 74

Figure: Page

13 Five-Minute Volumes Across Sensors F1A, F1C, and F1E on January 24, 1974......... 75

14 Tampa Moving Merge System: Instrumentation Subsystem............................ 77

15 Tampa Moving Merge System: Driver Display Subsystem............................ 82

16 The Elements of the Driver Display in the Tampa Green Band System.................. 83

17 Control Equipment Hardware for the Tampa Green Band System...................... 87

18 Mode Change Currently Implemented for the Tampa Green Band System...................... 97

19 IBM System/360 CSMP Program for the Analysis of Green Band Trajectories Under Variable Acceleration Profiles in the Stopped-Gap Operating Mode.................. 101

20 Computer Output from Stopped-Gap Band Trajectory Analysis Program..................... 102

21 Linear Tampa Ramp Geometry................... 106

22 Placement of Traffic Counters for Merge-Point Location Study......................... 112

23 Distribution of Ramp Vehicles Entering Freeway by Count Station, 7 A.M. - 11 A.M., December 13, 1972............................. 114

24 Per Cent of Ramp Vehicles Passing Count Stations, 3 P.M. - 7 P.M., December 13, 1972....................................... 115

25 Location of Merge Point for the Tampa System....................................... 118

26 Surveillance Area for Travel Time Study.. 120

27 Space-Time Diagram for Maximum Expected Speeds....................................... 124

Figure: Page

28 Space-Time Diagram for Minimum Expected Speeds.......................... 126

29 Space-Time Diagram for Mid-Range Speeds....... 128

30 Space-Time Diagram for the Location of Tampa Ramp Detector R3..................... 130

31 Evaluation Plan Flow Diagram................. 141

32 Public Opinion Questionnaire for Tampa Green Band System Evaluation................. 145

33 Scheme Used for Assignment of Field Sensor Channels to Input Hardware Buffer Words in the Tampa Green Band System.......... 147

34 Data Logging Routine Tape Block Format for the Tampa Green Band System............... 150

35 Subroutine Structure for TOGAP Data Reduction Software........................... 156

36 Output from Subroutine EVENT Showing Decoded Teletype Message, Field Sensor Activity, and Driver Display Data............ 160

37 Freeway Vehicle Tracking Output From TOGAP.................................. 168

38 Freeway Vehicle Trajectories by Vehicle Number................................ 170

39 Sensor Activity Summary from TOGAP........... 174

40 Freeway Vehicle Acceleration NOISE Output from TOGAP........................... 177

41 Distribution of Freeway Vehicle Velocities at F1............................. 180

42 TOGAP Output for the Analysis of Freeway Vehicle Lane Changing Upstream of the Merge Area............................ 181

Figure: Page

43 TOGAP Output Showing Distribution of Vehicle Travel Times on the Ashley Street Ramp........................... 184

44 Summary Output from TOGAP Green Band/Ramp Vehicle Tracking...................... 186

45 Pictorial Display of TOGAP Green Band/Ramp Vehicle Tracking...................... 190

46 Data for the Calibration of the Sonic Dectectors Used in the Tampa Green Band System.................................... 193

47 TOGAP Output from the Sonic Detector Analysis of Lateral Vehicle Displacements in the Merging Maneuver........................ 195

48 Flow Chart of Routine MODEXX................... 198

49 TOGAP Outputs for Green Band Control System Mode and Masking Activity.............. 202

50 Computer-Generated Plot of Ramp and Freeway Vehicle Trajectories Produced by TOGAP Software.............................. 205

51 TOGAP Outputs for the Distribution of Freeway Gaps Matched by Ramp Vehicles Detected at Sensor R1.......................... 208

52 Subroutine Calling Rates in the On-Line Control Program........................... 230

53 Operating Environment for the Green Band Control Program Simulator Illustrating Inputs, Logic Elements, and Outputs........... 234

54 Subroutine Structure for Green Band Control Program Simulator..................... 235

55 Scheme Used for TOGAP Data Storage in Green Band Simulation Routine.............. 237

56 Flow Chart of HVP Logic Used in Control Program Simulator..................... 240

Figure: Page

57 Flow Chart of Subroutine INSERT.............. 243

58 Flow Chart of Green Band Status Routine.................................. 245

59 Scheme for Filming Simulated Green Band Outputs........................ 254

60 Initialization Output from Green Band Simulator............................ 257

61 Band Output from Control Program Simulator................................ 260

62 Case I Data.............................. 276

63 Case II Data............................. 279

64 Case III Data............................ 281

65 Case IV Data............................. 282

66 Case V Data.............................. 284

67 Case VI Data............................. 285

68 Case VII Data............................ 287

69 Case VIII Data........................... 288

70 Case IX Data............................. 290

71 Band Output Showing GBS Operation Inhibited Except at Sensor Event Times........ 291

72 Schematic Diagram of Moving Merge Controller Using Micro-Computer Technology....... 310

73 Projected Configuration of Packaged Moving Merge Controller............................. 319

74 Photograph Taken from the Screen of a Surveillance Radar at Tampa International Airport Showing Freeway Vehicle Traffic on I-75 Across Tampa Bay........................ 334

Abstract of Dissertation Presented to the
Graduate Council of the University of Florida
in Partial Fulfillment of the Requirements
for the Degree of Doctor of Philosophy

OPERATING STRATEGIES AND RELATED PERFORMANCE EVALUATIONS FOR A MOVING MERGE CONTROL SYSTEM

By

Christian S. Bauer, Jr.

March, 1975

Chairman: Kenneth G. Courage
Major Department: Civil Engineering

In 1970, the Raytheon Corporation, under a contract with the Federal Highway Administration, conducted preliminary field tests on two types of moving merge control systems at a freeway entrance ramp on Route 128 in Woburn, Massachusetts. The tests demonstrated the operational feasibility of both systems, and established a driver preference for the green band system concept, which displayed bands of light moving along the ramp corresponding to acceptable gaps available in the freeway traffic stream for merging vehicles.

In 1972, the University of Florida began a joint research project with the Florida Department of Transportation involving the installation and evaluation of a green

band system on the Ashley Street entrance ramp to I-75 in Tampa, Florida. This ramp does not meet current geometric design standards, and a major objective of this project was to determine the feasibility of improving the operation of such sub-standard ramps with a moving merge control system as contrasted to the traditional approach of reconstruction.

Modifications and improvements to the Woburn site hardware and software used to install the Tampa system are described. System improvements suggested by operational experience in the public operation of the Tampa system are presented, including the development of new algorithms for on-line sensor calibration, green band propagation, and system mode control.

Techniques developed for the automated performance evaluation of ramp operations under the direction of a merging control system are described, and a trade-off analysis of existing system functions and requirements leading to a recommended hardware/software configuration for future merge control systems is presented.

CHAPTER 1
AN OVERVIEW

Introduction

Modern traffic engineering practice is concerned to a large extent with the solutions to problems arising from freeway congestion. Among these problems are questions relating to the diversion of vehicles in a traffic system to achieve balanced operation of existing facilities and roadways within the system, regulation of traffic flow characteristics on a given roadway to achieve specified operating characteristics, and methods for providing assistance to drivers using such facilities to reduce delays and provide additional safety margins.

The objective of providing driver assistance has been approached in freeway systems primarily through the use of ramp control systems. Figure 1 presents a chart of the hierarchy of freeway ramp control system strategies classified with respect to the sophistication of the control algorithm involved, and the degree of driver assistance provided to the ramp driver in the merging maneuver by each system. The earliest ramp control technique simply involved the closing of certain entrance ramps during periods of peak

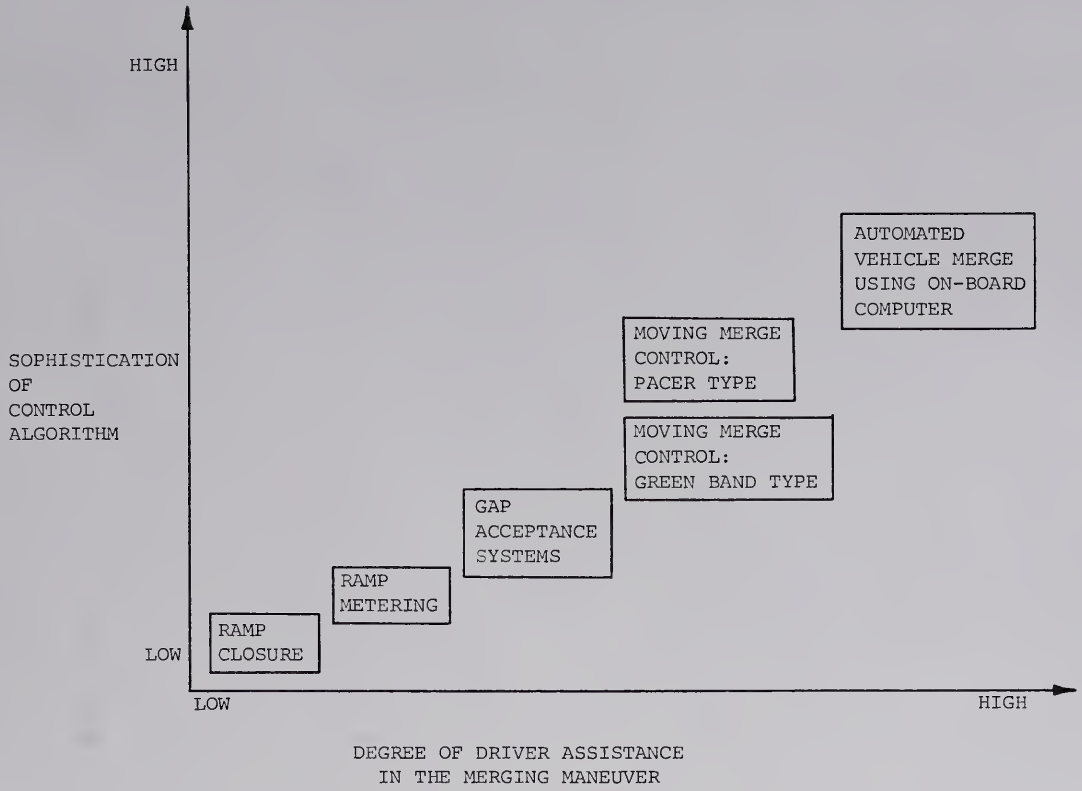

HIGH
SOPHISTICATION
OF
CONTROL
ALGORITHM
LOW
RAMP CLOSURE
RAMP METERING
GAP ACCEPTANCE SYSTEMS
MOVING MERGE CONTROL: PACER TYPE
MOVING MERGE CONTROL: GREEN BAND TYPE
AUTOMATED VEHICLE MERGE USING ON-BOARD COMPUTER
LOW
HIGH
DEGREE OF DRIVER ASSISTANCE
IN THE MERGING MANEUVER

Figure 1. Hierarchy of Freeway Ramp Control System Strategies

traffic flow. The primary concern was the regulation of total freeway traffic flow to achieve desired operating conditions, and the degree of assistance to ramp drivers in such systems was minimal. It could be argued, however, that once ramp drivers diverted from a closed ramp were able to gain access to the freeway by another route, they were themselves aided by the overall system of ramp closures, as the freeway traffic flow was maintained at levels consistent with efficient operation.

The next category of ramp control systems is one involving metering of vehicles onto the freeway from an entrance ramp. Early systems used police officers stationed at the entrance to the freeway ramps who were responsible for allowing a certain number of vehicles per minute to enter the freeway. The goals of such systems were to reduce queueing problems in the merge areas associated with such ramps and to prevent congestion at the freeway entrance point associated with the ramp. Advanced systems of this type typically use conventional fixed-time traffic control equipment to establish ramp metering rates in conjunction with conventional traffic signals to alleviate the need for human personnel stationed on the ramp, and can include features which make these systems traffic responsive, that is, having the capability to adjust metering rates to account for different observed flow patterns on either the ramp or freeway or both. Note that the sophistication of control algorithm in ramp metering systems is of necessity somewhat higher than that involved with the ramp closure systems, which simply involved, in most cases, mechanical barriers to the ramps or changeable message signs indicating that the ramps were closed.

Higher on the sophistication scale are the so-called stopped gap-acceptance systems whose operation is depicted in Figure 2. In such systems, sensors installed on the freeway upstream of the entrance ramp measure gaps in the freeway traffic, and activate a conventional traffic signal on the ramp at a time projected to allow the ramp vehicle to enter the freeway gap when it reaches the merge area. Such systems represent an attempt to fit the driver into available freeway gaps directly, and thus represent a considerable improvement in the potential for providing assistance they offer to ramp drivers. A shortcoming of gap-acceptance systems, however, is that they exert no control over the driver's actions once he has left the control signal area. Thus, assumptions are necessary on average driver performance in the acceleration maneuver between the time he leaves a signal and the time he is expected to reach the freeway gap and problems can arise if vehicle trajectories do not meet the expected characteristics.

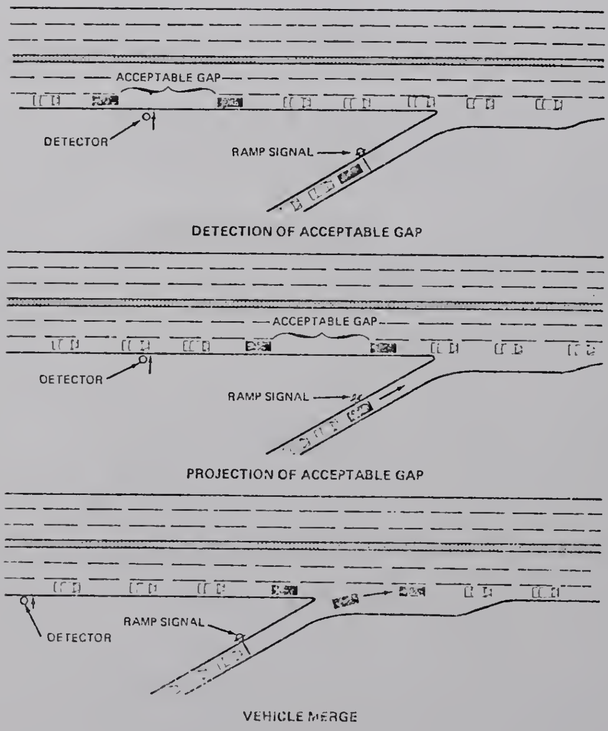


Figure 2. Illustration of Sequence of Operations in a Gap-Acceptance Merge Control System

To achieve additional dynamic control of ramp vehicles in the merging maneuver, another class of systems known as moving merge control systems has been developed, representing additional sophistication in the control algorithm as well as an additional potential for providing driver assistance in the merging maneuver. In these systems, gaps in the freeway traffic are detected as they are in gap-acceptance systems, but are then used to operate displays alongside the entrance ramp to guide the ramp vehicles into the freeway gaps. These systems provide additional information to the ramp driver over earlier systems, as they are typically designed to display a pictorial representation of how well the ramp vehicle driver is succeeding in his attempted merging maneuver. Two categories of moving merge control systems tested to date are depicted in Figure 1, respectively the Pacer-type system, which used a closed-loop algorithm, and the green band type, which was an advisory system using an open-loop control strategy. Each system concept will be reviewed in Chapter 2, but the positions of the systems in Figure 1 gives an idea of the results of research findings relating to their use. The green band system and Pacer system both represented additional assistance to ramp drivers over that associated with earlier gap-acceptance systems; the relatively higher degree of sophistication displayed in the Pacer system control algorithm over that used in the green band system did not materially increase its utility to ramp drivers over that provided by the green band system.

A possible future direction of ramp-merging control systems research is that pictured at the top right of Figure 1, which represents automated vehicle merge control systems using on-board computers in each vehicle. With this approach, information on freeway gaps is processed by a central computer and transmitted to a controller in each vehicle. Then, as a vehicle proceeds down the ramp, it is under the supervision of this equipment and the ramp driver can either follow control instructions displayed in the car or, in advanced systems, let the system control the position of the vehicle throughout the entire merging maneuver. While such systems have not yet been demonstrated, the continuing rapid development of computer technology and solid-state electronic systems makes their operation technically feasible in the near future.

Previous Research

A considerable body of literature exists on the subject of freeway and ramp control systems and related areas of concern. Wattleworth [1] discussed some of the basic theoretical considerations in the operation of freeway systems and discussed several control schemes for the alleviation of freeway congestion, including a method of using linear programming to determine the optimum metering rate of vehicles entering a congested freeway. Drew [2] studied freeway traffic congestion using a variety of mathematical models of freeway traffic flow and applied the results of this work to data obtained from the Gulf Freeway in Houston, Texas. Early field work in freeway ramp control was discussed by May [3] who treated work done on the Congress Expressway in Chicago involving the implementation and evaluation of ramp closure and ramp metering based on occupancy measurements taken upstream of the entrance ramp, and by Gervais [4] who discussed work done on the John C. Lodge Freeway in Detroit involving ramp closure experiments dating back to 1960. Both of these approaches involved the use of humans in the control loop to make the appropriate metering decisions and did not attempt to automate the control process.

In 1963 a research project was begun by the Texas Transportation Institute sponsored by the Texas Highway Department and the U. S. Bureau of Public Roads (now the Federal Highway Administration) with the objective of "developing a criteria for the design and operation of automatic surveillances and control systems which would permit the attainment of acceptable levels of service on heavily traveled urban freeways during peak period of demand" [5, p.2]. This was the beginning of a period of intensive research activity in ramp control theory and application by the Texas Transportation Institute throughout the decade of the 1960's and resulted in many research studies which have contributed materially to the general understanding of the behavior of freeway traffic systems [6-18]. Ramp metering studies on the Gulf Freeway were conducted in 1964 using police officers stationed on the ramp as the control element. System development continued with the installation of traffic signals and associated advisory signs on eight ramps over a 6.5-mile section of the Gulf Freeway.

In early 1966, a prototype merging control system was installed on the Telephone Road Interchange entrance ramp on the Gulf Freeway using a hardware controller which was traffic responsive and completely automatic. This special-purpose analog computer was one of the first examples of hardware developed specifically to perform the control functions of a merge control system. The equipment had the capability for using either of two basic ramp control strategies to assist in the merging process. The first of these was the gap acceptance mode of control which searched for freeway gaps upstream of the merge area and activated a traffic light on the ramp at a time calculated to allow the ramp vehicle to arrive at the merge area at a time corresponding to the expected time of arrival of the freeway vehicle at the same location. The second control strategy implemented was a demand-capacity mode of operation which adjusted the metering rate of a ramp signal in accordance with the measured freeway flow rate upstream of the entrance ramp location to keep the total freeway volume downstream of the ramp at or below freeway capacity at that point, thus reducing the probability of freeway congestion developing at that location.

Hardware development continued in the Gulf Freeway Project with the installation of first-generation production controllers based on the earlier prototype hardware in October, 1967, and improved second-generation controllers in November, 1968. The latter generation projected gaps in the freeway traffic based on the measured speed of the lead vehicle of the freeway gaps rather than on the speed range of the average freeway vehicle speed as was the case with their first-generation counterparts. These units automatically selected one of four sets of detectors on the freeway to use for gap projection based on the prevailing freeway speed at the time. Capabilities were also provided for multi-vehicle merges and for monitoring the travel time of a vehicle released from the ramp signal to account for trucks and other slow moving vehicles which did not clear the merge area in the expected time. Given that such a condition was detected, the system could then hold the ramp signal in red until the previous vehicle had cleared the merge area, thus providing an additional safety factor in the merging operations.

In July of 1967, an IBM 1800 process control computer was installed in the Gulf Freeway Control Center to provide a capability for research into methods of "system" control of the freeway as opposed to the individual ramp control that had been possible with the special purpose single-ramp controllers. Experimentation was begun with computer control of the ramps in March of 1968. Two factors associated with the use of the digital computer as a ramp control system led the researchers to the hypothesis that "even isolated entrance ramps can be better controlled with digital equipment" [17, p. 38]. These factors were (1) the ability to change the control philosophy of a digital process controller by simply changing the stored program, and (2) the fact that the process inputs and outputs associated with a ramp control system are themselves digital signals, e.g., the system inputs are in the form of relay contact closures from the detectors in the field and the control signals to be sent to the field are in the form of on-off commands or discrete state change commands to the various ramp signals and displays.

Research work on other freeways was proceeding in parallel with the initial development work on the Gulf Freeway in Houston. The Michigan Department of State Highways and the U. S. Bureau of Public Roads had sponsored earlier research on the John C. Lodge Freeway in Detroit. This project evolved into a multi-state cooperative effort called the National Proving Ground for Freeway Surveillance, Control, and Electronic Aids [11]. Formal research work of the National Proving Ground ended in 1966 and the American Association of State Highway Officials assumed the sponsorship of the project on the Lodge Freeway placing it in the National Cooperative Highway Research Program (NCHRP). The program was designated NCHRP Project 20-3, and began on December 16, 1966, with the Texas Transportation Institute serving as the research agency. Previous work done at the site had included the installation of television cameras and an automatic detection system for monitoring of the freeway. A Control Data Model 8090 computer was installed with sufficient capacity for controlling eight ramps on the downtown Detroit area using both the gap acceptance and demand capacity control modes. The control strategy for the system was based on the linear programming technique developed by Wattleworth [1] and modified for use in an online control strategy. The linear programming model determined for each five-minute control period the optimum metering rates on each of the entrance ramps in the controlled area. With the control system in operation, a significant improvement in the operational efficiency of the freeway system was observed, including a reduction in the average travel time of a vehicle through the 8.5-mile freeway section during peak periods from 29 minutes to 17 minutes [11, p. 23].

Research continued in advanced merge control systems at the Texas Transportation Institute for the next few years including the development and testing of the first "moving merge" ramp control system [16]. Traditional ramp control systems have as a primary objective the reduction of freeway congestion in periods of peak demands. A secondary objective of such systems is to assist the individual ramp vehicle drivers in carrying out their merging maneuvers. Gap acceptance systems can accomplish both objectives by detecting acceptable gaps on the freeway and attempting to fit the ramp vehicles into these gaps. During periods of peak demand the ramp vehicle arrival often exceeds the availability of acceptable freeway gaps and it becomes necessary to delay ramp vehicles until suitable gaps are available. However, in off-peak conditions there are typically more freeway gaps available than there are ramp vehicles to fill them; therefore, stopping every ramp vehicle as a part of the ramp control algorithm can introduce unnecessary delays to the ramp vehicle traffic. Therefore, a basic design goal for moving merge control systems is to achieve the matching of ramp vehicles and freeway gaps without the need for stopping all ramp vehicles.

The Texas Transportation Institute prototype moving merge control system was designed to test the technical feasibility and driver acceptance of the moving merge concept. Tests were conducted on a simulated entrance ramp marked out on a concrete runway of the Texas A&M University Research Annex. Four standard three-face traffic signals were used as the control element alongside the ramp. They were placed at 150-foot intervals with the first signal 600 feet from the nose of the ramp. The signals were controlled by a standard fixed time signal controller with the cams arranged to provide the desired timing sequence for the lights. An advisory speed sign was placed on the ramp 525 feet upstream of the nose between the first two signals. The indication on this sign was changed manually. The radio communication system was used to transmit freeway speed information to the ramp vehicle driver. Tests were conducted and evaluated on the basis of whether the ramp vehicle had been placed in an acceptable position for the merging maneuver or not. A constant gap for the simulated freeway vehicles of 4 seconds was used for all test runs. Drivers of the leading and trailing cars of the freeway gap were instructed to maintain a given velocity and spacing vehicle trajectory data were obtained by loop detectors placed on the ramp acceleration lane and outside freeway lane. Loop actuation data were recorded and used to prepare time-space diagrams for each merge. The feasibility of the moving merge concept was demonstrated by the experimental runs conducted. In one series of tests the ramp drivers were placed in a position to merge successfully 70% of the time and in another series using an instrumented vehicle, the success rate was better than 50%. Recommendations were made for installation and testing of a moving merge control system on an actual freeway entrance ramp to test the concept under real-world conditions. This recommendation led eventually to the systems designed and implemented by the Raytheon Corporation which are discussed later in this paper.

A number of researchers reported work in what might be called the systems area of ramp control from 1966 to the present [19-33]. Weiner [22] modeled the velocity profiles of freeway shoulder lane and ramp merging vehicles as stochastic processes, and developed a method of computing the optimum instant of release of a ramp vehicle in a gap acceptance control system to insure the maximum probability of its arrival at the merge area in synchronization with the freeway gap. Yagoda and Pignataro [25] developed relationships between merging capacity and system parameters for several gap-acceptance control systems operating philosophies. Klee [33] developed an algorithm for synchronizing ramp vehicles into freeway gaps based on a consideration of the interactions between the freeway vehicles defining a gap as described by car following theory.

Considerable work in the general area of traffic flow theory exists of which the case of ramp vehicle/freeway vehicle interactions in the merging process is a subset. Much of the early work in this area [34-37] concerns the dynamics of vehicle movement under free flow conditions. Jones and Potts [38] developed what has become a widely used parameter for the description of the quality of vehicle flow along a roadway. They suggested the use of a quantity called "acceleration noise," defined as the root-mean square value of the average acceleration experienced by a vehicle over a period of time. Conceptually a vehicle with a low acceleration noise may be considered to be operating under conditions of smooth traffic flow, and conversely, a vehicle with a high acceleration noise is typically in a situation where the operations of other vehicles have a great effect on its own motion. Other researchers [39-55] have treated other areas of traffic flow theory. As is the case with other scientific disciplines, much research work has been devoted to specific problems in areas and no general unified theory of traffic flow has yet been developed which will account for all of the conditions of vehicular traffic flow, density, and speeds experienced in the modern traffic environment.

The question of the existence, stability, and distribution of gaps, defined as the distance in space or time between two successive vehicles in a freeway traffic stream, is of crucial importance in the design and operation of ramp merging control systems. Oliver [56] discussed basic methods of looking at the statistical flow processes that generate the observed gaps in a traffic stream. One approach was to focus one's attention on the major stream of traffic in order to then study a variety of flow and storage situations that are created by various crossing or merging traffic streams. The second approach was to formulate the statistical process in the major stream of traffic in terms of observed conditions in the minor stream. An example is the wait of a random vehicle arrival at an intersection for a gap of a certain size in the major stream. Solberg and Oppenlander [57] treated the question of lag and gap acceptances at stop-controlled at-grade intersections in a paper of limited usefulness in the analysis of freeway merge control systems, but mentioned here for its interesting discussion of the comparison of results obtained from three different methods of accumulating the information on rejected and accepted gap distributions. Drew [58] discussed the data collection and reduction necessary to determine the gap acceptance and merging delay characteristics for the six entrance ramps to be controlled in the Gulf Freeway Surveillance and Control Project mentioned earlier. Merging vehicles were classified into two groups, (1) those in which the driver rejected gaps before finally accepting the gap, and (2) those in which the driver of a ramp vehicle accepted the first gap observed at the merge area. The former was referred as stopped vehicles and the latter as moving vehicles. The critical gap for stopped vehicles was found to be some 20% higher than that for moving vehicles. In addition, he concluded that the "critical gap," defined as a gap whose probability of acceptance is 0.5, for the merging maneuver from an entrance ramp is independent of the freeway volume but was apparently affected by ramp geometrics and ramp control measures. Queueing theory was used to derive expressions for average waiting time for a ramp vehicle before merging and the expected queue length on the ramp waiting to merge. Applications of the derived data controller settings for ramp control systems were discussed. Miller [59] presented a comparative study of selection of nine different methods for analyzing gap acceptance data. Pahl [60] used data from aerial photographs to determine the average space and time sizes of accepted gaps and gap maneuvers for exiting freeway vehicles close to their intended off-ramp and for through vehicles as a function of the distance from the off-ramp. Again, while this paper is of limited usefulness in the analysis of on-ramp control systems, it is interesting with respect to the insights it provides into the behavior of freeway vehicles.

The important question of the "stability" of a freeway gap, which can be defined as the probability that a gap measured at a certain size will remain that size at a point downstream of the initial observation point was treated in some detail by Buhr [61], and Munjal, Hsu, and Lawrence [62]. The first paper developed regression equations for gap size downstream of a given freeway location as a function of the initial size of the gap when first observed and of the speed of the gap when first observed. The latter paper develops analytical expressions for errors in gap production and speed estimation from experimental data obtained from aerial photographs. The analyses discussed include the effects of differing sensor scan rates and detector location on the gap size predictions. Consideration is also given to the relative accuracy of single-loop detectors versus double-loop detectors for the gap prediction process. The usefulness of the previous two papers related directly to the question of the type and number of detectors to be used in a freeway control system to achieve some given level of gap prediction accuracy.

Results from the classical queueing theory of operations research are often useful in the design of a freeway control system as they can give some indication of relative expected system performance characteristics as a function of various control parameters as mentioned earlier in the Drew paper [58]. Other researchers who have treated the highway merging process as a queueing system include Evans, Herman, and Weiss [63], Jewell [64], and Marcus [65].

Since merge control systems use information on freeway vehicles to control the movements of ramp vehicles, it is important to consider how these data were obtained. A number of researchers have studied the question of detector performance in the literature. Stern [66] considered the use of magnetic loop detectors embedded in the road surface to collect data on vehicle characteristics. Christensen [67] discussed the use of a computer and vehicle length detectors at signalized intersections. While this work does not relate directly to freeway vehicles, it is of use in the computation of ramp vehicle queues and delays, which may serve as control inputs to advanced freeway ramp control systems. Detector accuracy is discussed, and testing procedures reviewed, in a report by the Sperry Rand Corporation [68]. Courage [69] discusses electronic measurements of traffic variables on a multi-lane freeway using a combination of sonic detectors and optical detectors to measure traffic stream parameters. Gazis and Foote [70] present a calibration technique for magnetic loop detectors using vehicle data obtained from optical presence detectors as a basis. Gordon, Dodge, and Scott [71] discuss the surveillance aspects of a computer controlled traffic system. Although the paper is concerned with Washington, D. C., Urban Traffic Control System, it is nevertheless interesting from the standpoint of its discussion of the transmission of vehicle sensor data over leased communication lines, and its treatment of techniques for the correction of instrumentation bias errors. The general theme of sensor error analysis is continued is contined in papers by Pahl [72], Huckins [73], and Mikhalkin, Payne, and Isaksen [74]. The latter paper treats the question of the estimation of speed information from single-loop detectors, and concludes that the use of estimation techniques based on the processing of sensor on-times associated with the passage of individual vehicles rather than on period averages can reduce the errors associated with computed speeds.

Research Objectives

The University of Florida began a research contract with the Florida Department of Transportation in 1972 involving the installation and operational evaluation of a green band type moving merge control system on the Ashley Street entrance ramp to I-75 in Tampa, Florida. The scope of this dissertation includes the following areas of research performed in conjunction with this contract:

1. Systems analysis and design engineering activities performed to adapt the proto-

type Woburn site hardware and software to the specialized requirements of the Tampa site, and to correct operating problems experienced with the earlier system.

2. The identification and development of computerized techniques for ramp system performance evaluation under existing conditions and after the installation of the merge control system, including both the on-line recording of control system sensor, mode, and field display activity, and the subsequent off-line analysis of such data.

3. Consideration of improved hardware and software design factors for use in future implementations of moving merge control systems.

Research Profile

Chapter 2 discusses the green band system and Pacer system moving merge control systems originally developed by the Raytheon Corporation and tested on a freeway entrance ramp in Woburn, Massachusetts in 1970. Design elements of these systems are reviewed relating to the need for changes in the later Tampa system.

In Chapter 3, the Tampa Green Band System, changes made to the Woburn system hardware and software used to implement the green band system concept at the Tampa site are discussed. These changes were of three basic categories:

1. Changes required by the Tampa site geometry, which is considerably different from that which existed at the Woburn ramp.
2. Corrections made to known and anticipated problems in the Woburn control programs.
3. Operating improvements which represented extensions to the capabilities of the Woburn system.

Chapter 4 discusses various techniques devised for the analysis of the Tampa system performance, with emphasis on the computerized schemes used for recording data on-line by the control system, and for the subsequent off-line analysis of this information. The development of computer software to implement these functions is described, and examples of processed system operating data are discussed.

Chapter 5, Design Considerations for Future Merge Control Systems, discusses three basic areas, including known deficiencies of the current Tampa system, theoretical requirements and improvements that could be implemented in advanced merge control systems, and the development of standalone controller hardware packages for merge control systems.

Conclusions resulting from the research work comprising this dissertation and suggested areas for future research involving moving merge control systems are discussed in Chapters 6 and 7.

CHAPTER 2
BACKGROUND

Prototype Merge Control Systems Tested in Woburn, Massachusetts

In 1967, the Traffic Systems Division of the Bureau of Public Roads began a program with the Raytheon Company to "study, design, and fabricate a dynamic merging control system, and to study the problems of adaptive control traffic flow in the urban freeway corridor" [75, p. 108]. An urban freeway was defined to be the freeway itself plus as many of the adjacent arterial streets, both parallel and perpendicular to the freeway, as could be considered to be supporting traffic flow in the same general direction as the freeway. The following design requirements were established for the hardware to be developed in the study [75, p. 109]:

1. Ramp vehicles were not to be stopped unless absolutely necessary.
2. Dynamic control over ramp vehicles was to be used to regulate the time of arrival at the ramp nose of the merging vehicle.
3. If circumstances caused the formation of a queue on the ramp, it was not to be allowed

to extend back to the city streets feeding the ramp.

4. The gaps on the freeway were to be detected early enough to initiate a controlled merge.
5. The merging maneuver was to be monitored and the system made responsive to changes such as loss of the freeway gap and non-compliance of the ramp vehicles with the control signals displayed by the system.
6. Perturbations in freeway flow (forced merges) were to be minimized.
7. The system was to keep track of vehicles on the ramp and to be responsive to the onset of congestion.
8. The system was to be made fail-safe.
9. The system was not to require a human operator for normal operation.

Consideration of the above objectives resulted in several differing hardware system concepts to provide control of a ramp-side driver display [76-85]. Two candidate display concepts were designed and tested. The first was based on a closed-loop control configuration and referred to as the Pacer system, and the second was based on an open-loop control system strategy, referred to as the green band system. Figure 3 shows the elements of the Pacer system. Seven double-loop detector stations were placed in the right-hand lane of State Route 128 near the town of Woburn, Massachusetts, upstream of the entrance ramp from Route 38. Communications wires were run from these detector stations to a Raytheon Model 703 computer located in a control center in a mobile trailer parked near the ramp. Freeway detector information was processed and used to project a single moving green light alongside the left side guard rail of the ramp. This information was displayed on 78 single-lens green traffic signals spaced eight feet apart. Eleven double-loop detector stations were used on the ramp itself to monitor and track the progress of ramp vehicles as they moved through the system. The relationship of the time-space position of each ramp vehicle with respect to its pacer light was monitored and used in conjuction with the reduced freeway data to control the future motion of the pacer light. Thus, the system control concept used in the Pacer system was closed-loop in nature, as the measured information on the position of the ramp vehicles was fed back to the system and used to update the prior display.

A second hardware configuration for a moving merge control system was evaluated in Woburn. This was the green

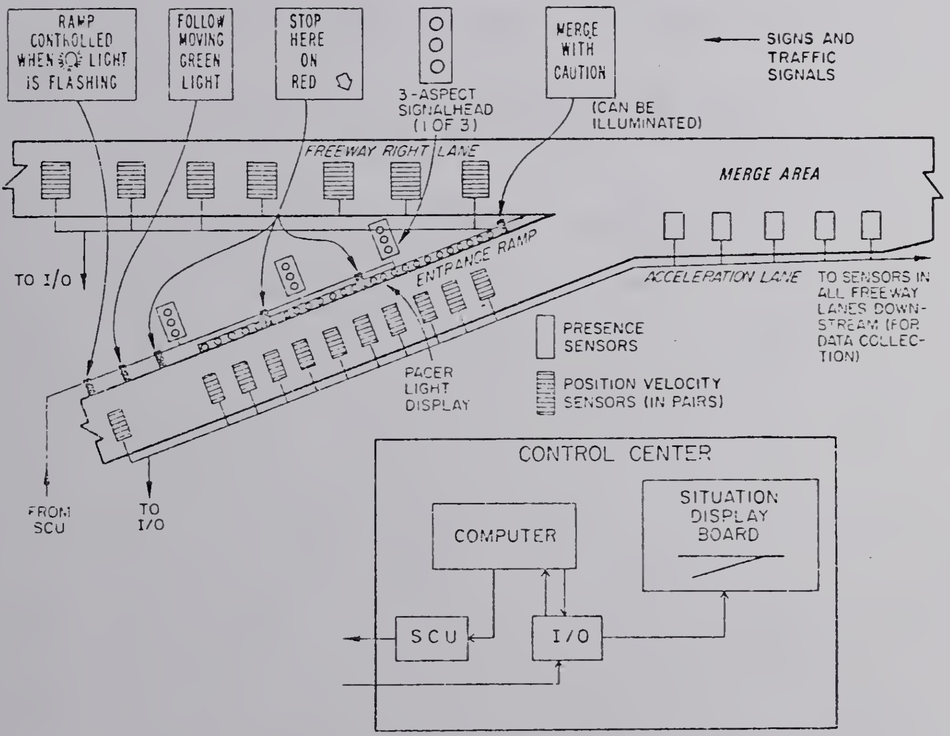


Figure 3. Schematic Diagram of the Raytheon Corporation Pacer Moving Merge Control System

band system, which was to provide no direct adaptive control of ramp vehicles, but rather was designed to provide a visual indication of the existence of the acceptable gaps in the freeway traffic stream which could then be used as advisory information for vehicles on the ramp. Figure 4 shows the Woburn Green Band System. The same sensor configuration was used on the freeway for the green band system as that used in the Pacer system. The sensors on the ramp were left in position but were not used as part of the control philosophy, and no information was provided to the control algorithm on the position and motion of ramp vehicles in the green band system. As the green band system concept was preferred by more of the drivers using both systems than was the Pacer [86], its use was recommended in future merge control system implementations and relevant details of its operation will be described here to provide a framework for the consideration of the Tampa Green Band System Project.

Green Band System Operating Modes

To meet the requirements for responsiveness to the onset of congestion mentioned earlier as a design constraint in a freeway ramp system, the green band merge control algorithm used in Woburn had three different operating modes. The standard mode of operation was the so-called moving mode

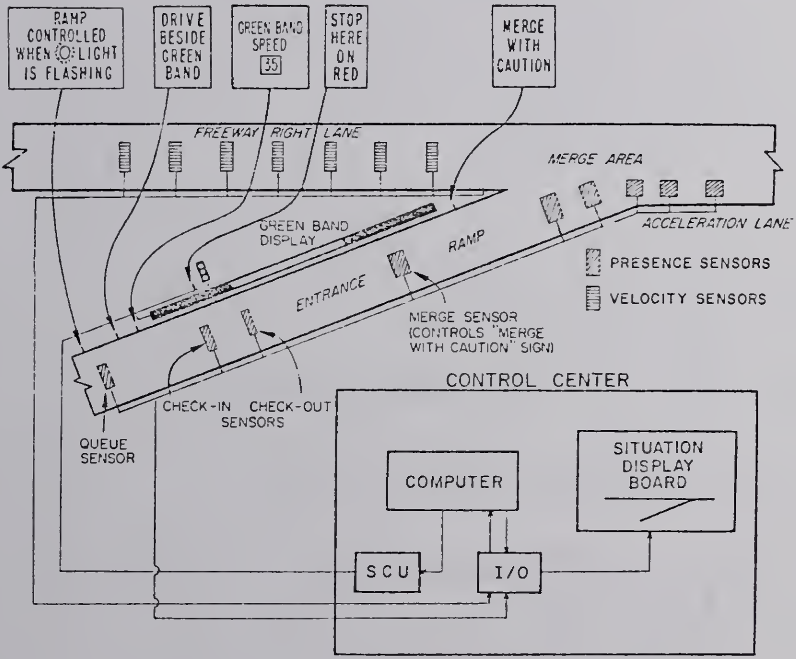


Figure 4. Schematic Diagram of the Raytheon Corporation Green Band Moving Merge Control System

Source: [86]

(MM), which projected moving bands of green light along the ramp display in accordance with gaps of acceptable length detected on the freeway. It is important to note that this was an open-loop control system, and that the motions of the ramp vehicles were not monitored with respect to providing information to the control system. The bands of light on the display were projected in accordance with available gaps only.

With the onset of freeway congestion detected by a reduction in the average detected velocity of the freeway vehicles at the last sensor station upstream of the merge area, the green band system changed to a stopped-gap acceptance (SG) mode of operation. In this mode, all ramp vehicles passing through the system were stopped at a standard traffic signal located approximately one-third down the length of the green band display. This system then searched for an acceptable gap for the ramp vehicle, and if one was found, released the ramp vehicle by turning the light green and projecting a green band of constant length down the display in such a fashion as to guide the merging vehicle into the proper position for merging. Provisions were made to release the ramp vehicle from the light without an accompanying green band if a specified maximum wait time in the red phase at the signal had been exceeded. This mode of operation represented an implementation of the earlier work conducted by the Texas Transportation Institute and other research groups in the area of stopped-gap acceptance. The unique feature of the Woburn system, however, was its use of the green band display to guide the ramp vehicles to the merge area, as the earlier systems had no means of controlling ramp traffic other than a standard traffic signal used to hold vehicles until a suitable gap had been located [87].

A third mode of operation was provided, the stop metering (SM) mode of operation. In this mode, ramp vehicles were stopped at the traffic light on the ramp and released at a fixed metering rate determined by constant values in the control program. This mode of operation was entered when freeway velocities indicated the onset of heavy congestion on the freeway area, and was similar to earlier work in fixed time metering used at a number of other installations involving ramp control projects [3].

The system had a fourth mode, representing an initialization phase which was entered when the system was initially activated each day, or stopped vehicles were detected in the ramp merge area. This consisted of a 15-second period during which freeway vehicles were tracked to establish data tables for subsequent use by the green band program, and during which the ramp display consisted only of a flashing amber indication at the stop light to indicate a proceed-with-caution condition to the ramp vehicle drivers.

To accomplish the objectives of automatic operation, the Woburn Green Band System was given the capability of automatically switching between the various operating modes in response to the changing freeway traffic conditions. Sensors downstream of the merge area in the right-hand freeway lane were used to measure total freeway volume across the roadway. Problems were encountered with reliability factors involving these sensors in Woburn, and the program logic designed to switch operating modes based on volume was disabled, as will be discussed in the next chapter on the Tampa Green Band System. Control logic to command mode transitions based only on average freeway speeds measured upstream of the entrance ramp was used to achieve the goal of system operation without human intervention during normal conditions.

Woburn Green Band System Operation

A flow chart of the computer subroutines in the on-line control program for the Woburn Green Band System appears in Figure 5. All control software for the Woburn Green Band System was written in the basic assembly language code for the Raytheon 703/704 Series Computers. In Figure 6, the operational task of each program is outlined in the sequence that the programs are called. The functioning of each program is discussed below.

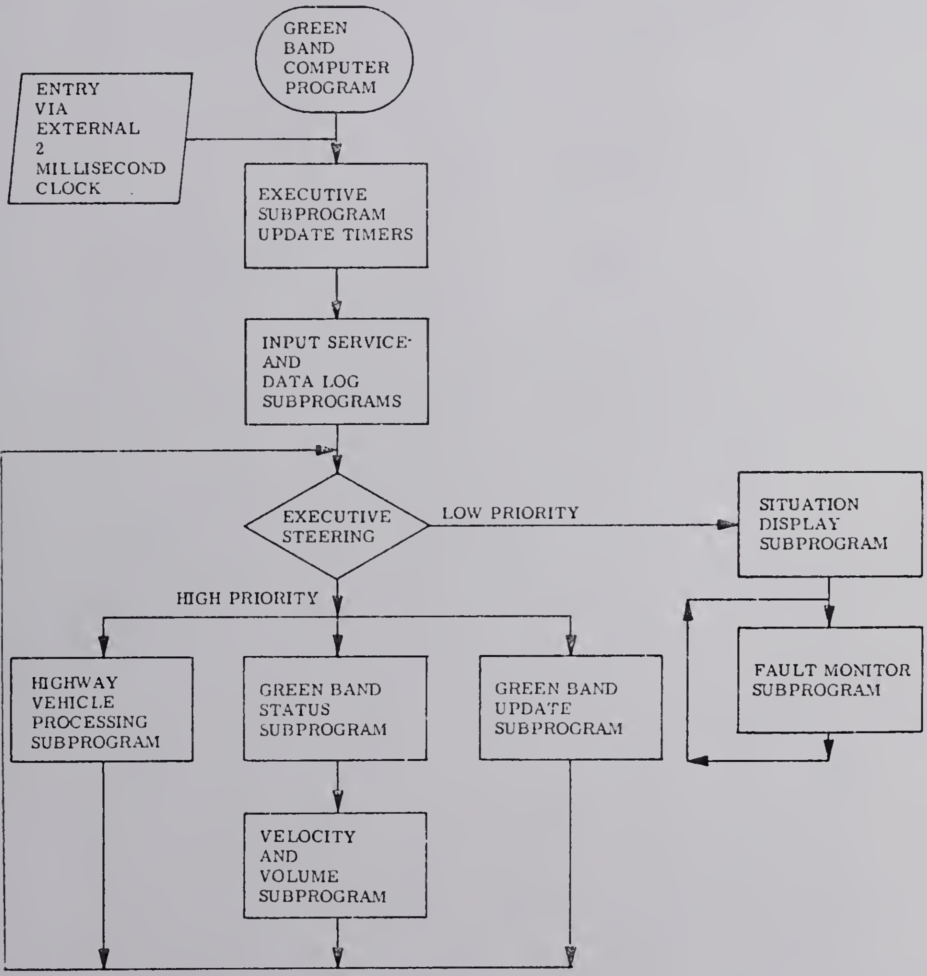

GREEN BAND COMPUTER PROGRAM
ENTRY VIA EXTERNAL 2 MILLISECOND CLOCK
EXECUTIVE SUBPROGRAM UPDATE TIMERS
INPUT SERVICE AND DATA LOG SUBPROGRAMS
EXECUTIVE STEERING
LOW PRIORITY
SITUATION DISPLAY SUBPROGRAM
FAULT MONITOR SUBPROGRAM
HIGH PRIORITY
HIGHWAY VEHICLE PROCESSING SUBPROGRAM
GREEN BAND STATUS SUBPROGRAM
GREEN BAND UPDATE SUBPROGRAM
VELOCITY AND VOLUME SUBPROGRAM

Figure 5. Green Band System Control Software Flow Chart

Source: Green Band Design, Vol. VIII, Merging Control System Final Report, Report No. ER70-4200, Equipment Division, Raytheon Company, Sudbury, Massachusetts, October, 1970, p. 4-2.

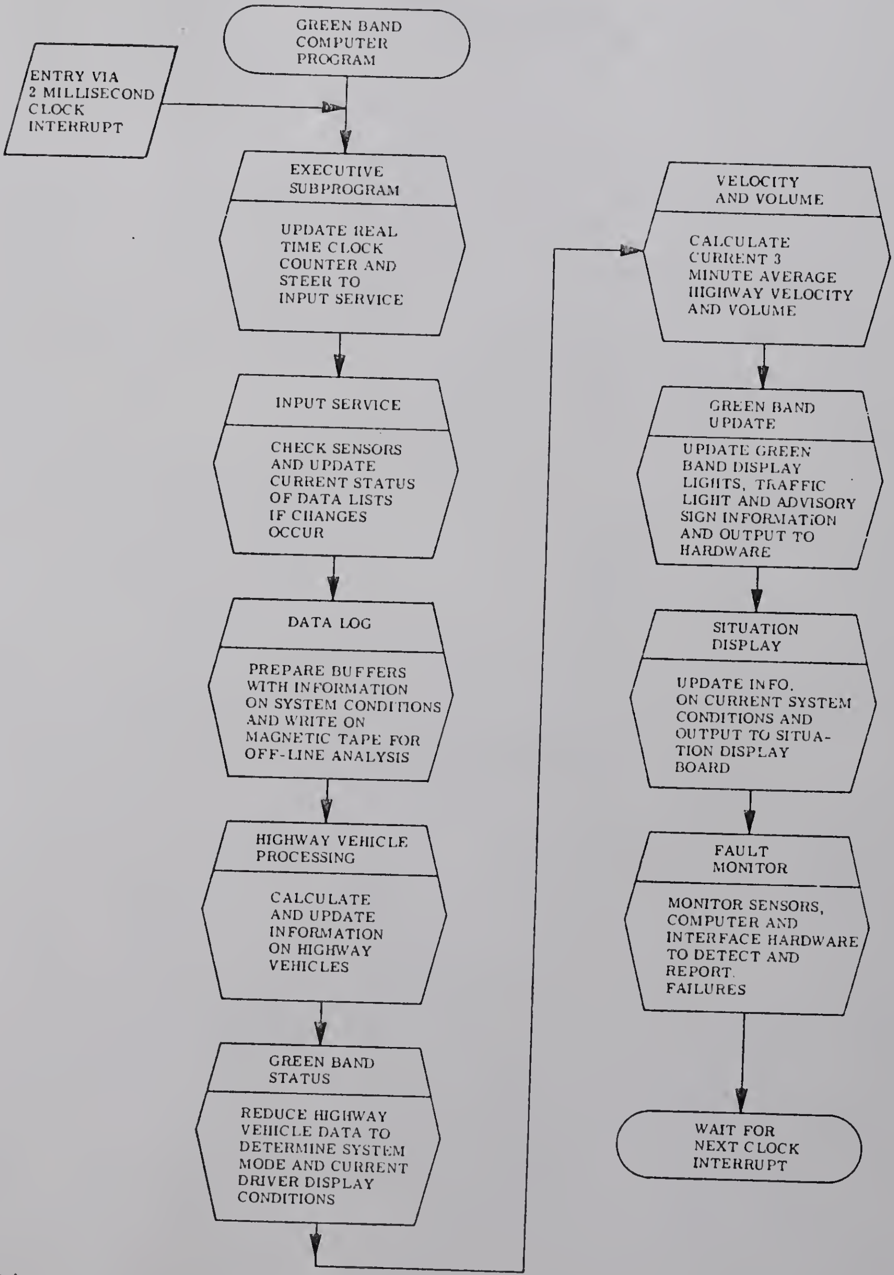

GREEN BAND COMPUTER PROGRAM
ENTRY VIA 2 MILLISECOND CLOCK INTERRUPT
EXECUTIVE SUBPROGRAM
UPDATE REAL TIME CLOCK COUNTER AND STEER TO INPUT SERVICE
INPUT SERVICE
CHECK SENSORS AND UPDATE CURRENT STATUS OF DATA LISTS IF CHANGES OCCUR
DATA LOG
PREPARE BUFFERS WITH INFORMATION ON SYSTEM CONDITIONS AND WRITE ON MAGNETIC TAPE FOR OFF-LINE ANALYSIS
HIGHWAY VEHICLE PROCESSING
CALCULATE AND UPDATE INFORMATION ON HIGHWAY VEHICLES
GREEN BAND STATUS
REDUCE HIGHWAY VEHICLE DATA TO DETERMINE SYSTEM MODE AND CURRENT DRIVER DISPLAY CONDITIONS
VELOCITY AND VOLUME
CALCULATE CURRENT 3 MINUTE AVERAGE HIGHWAY VELOCITY AND VOLUME
GREEN BAND UPDATE
UPDATE GREEN BAND DISPLAY LIGHTS, TRAFFIC LIGHT AND ADVISORY SIGN INFORMATION AND OUTPUT TO HARDWARE
SITUATION DISPLAY
UPDATE INFO. ON CURRENT SYSTEM CONDITIONS AND OUTPUT TO SITUATION DISPLAY BOARD
FAULT MONITOR
MONITOR SENSORS, COMPUTER AND INTERFACE HARDWARE TO DETECT AND REPORT FAILURES
WAIT FOR NEXT CLOCK INTERRUPT

Figure 6. Green Band System Control Software Function Diagram

Executive Subroutine

The executive subroutine schedules the calls to the individual subprograms making up the green band software system. It is entered at the time the program is first turned on or restarted, and transfers to initialization entries at each of the component subroutines to set up data tables in preparation for the next run. Then, as the system is operating, the executive program is interrupted by an external hardware clock at a rate of 500 times per second (representing a cycle time of 0.002 seconds). Upon each entry to the executive from an interrupt, the first action is to call the input service routine (ISR) which is co-located in core with the executive program. ISR reads four input words from the field containing the loop detector data and prepares tables of time reports for vehicle crossings at these sensors. At the end of input service routine activity, the executive program calls the data logging program to record any sensor changes on magnetic tape for subsequent off-line analysis. The executive program then schedules calls to the various system subroutines by comparing their next scheduled starting time with the current value of the system time word, and transferring control to the various routines if appropriate. Thus, in practice, the executive routine has no input or output variables of its own except timing information, and its outputs are simply calls to the various subroutines of the green band system in the proper sequence.

Input Service Routine

The input service routine (ISR) reads four 16-bit data words containing the field sensor input bits from an input/output hardware interface. These four words are compared with their previous values (e.g., the values read at the last interrupt) and any bit-level changes are processed individually by the ISR. Tables of data are maintained for each of the seven freeway sensor stations. When a new sensor data list is completed, containing times of entry and exit of a freeway vehicle at the detector loops in a station, a flag word is set by the input service routine to indicate a requirement for subsequent processing by the highway vehicle processor routine (HVP).

Highway Vehicle Processor Program

Consider the scheme used by Raytheon to identify the time of vehicle arrivals and departures at each loop of double-loop velocity sensor, as indicated in Figure 7. Time T3 represents the time at which the vehicle was observed to have crossed the leading edge of the first loop, T4 represents the time at which the vehicle was reported to have left the first loop, T1 represents the time the vehicle arrival

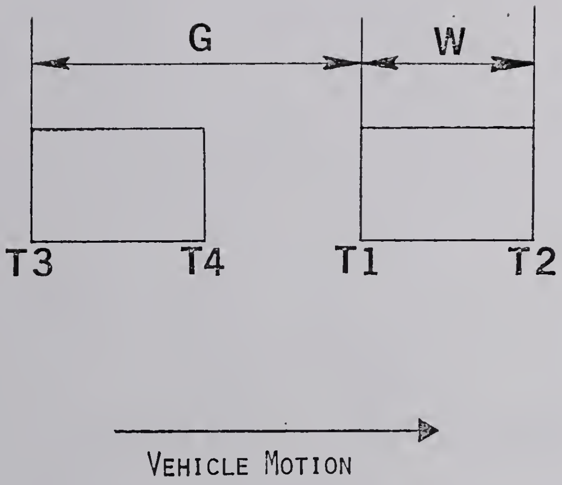


Figure 7. Illustration of Scheme Used by Raytheon for the Identification of Double-Loop Sensor Event Times

was noted at the second loop, and T2 represents the time at which the vehicle was reported to have left the second loop. The distances G and W represent respectively, the length in feet from the leading edge of the first loop to the leading edge of the second loop, and the width in feet of the second loop.

The input service routine is responsible for processing vehicle sensor event data into tables of time values for each sensor which then serve as the input to the HVP routine. Data for each vehicle passing through a double loop sensor consist of a sensor status word indicating the current state of the sensor data lists (e.g., are they full, empty, or representative of a vehicle overdue at the next sensor downstream), and information on the T1, T2 and T3 values for the current vehicle in the sensor. Also stored is a time difference Δ, representing the transit time of that particular vehicle from the leading edge of the first sensor to the leading edge of the second sensor. The processing of completed sensor data proceeds as follows:

1. The time of vehicle arrival at the leading edge of the second loop, as represented by the T1 data value passed from the input service routine, is stored as the time of completion of the sensor report for that particular vehicle.

2. The estimated time of arrival (ETA) of the highway vehicle at the downstream merge point is now computed. The expression for this value is ETA = T1 + (Δ*S/G), where S is the distance from the sensor to the merge point. The result of this calculation is ETA_{now} for the current vehicle. If this value for ETA_{now} is less than that for the ETA computation performed for the last vehicle, ETA_{last}, the assumption is made that the current vehicle is moving faster than the previous vehicle, and an application of the law of conservation of vehicles is made, resulting in the assumption that the current vehicle will slow down to avoid overtaking the last vehicle. In this instance, a "highway vehicle minimum time spacing" constant is added to the previous vehicle's ETA value to establish the ETA for the current vehicle. That is: $ETA_{now} = ETA_{last} + H$, where H = 0.8 sec. in the Woburn Green Band System.

3. The velocity of the freeway vehicle at the current sensor is computed by the expression $V = G/\Delta$ which results in a value representing the velocity in feet per second for the vehicle. If the computed value for this velocity is greater

than 120 feet per second, or less than 5 feet per second, the assumption is made that the calculations have a numerical error problem for this case and the vehicle is ignored until it passes the next sensor downstream. This was the factor which caused the Woburn Green Band System to break down in terms of its ability to accurately project freeway vehicle motion during times of heavy freeway congestion and associated low-speed operation [88].

4. The vehicle length (in time) is computed for the current freeway vehicle by using the expression $L = (T2 - T1) - (W/V)$. The first term in this expression represents the occupancy time of the vehicle in the second loop of the freeway sensor and the second term of the computation represents a correction factor to the occupancy time which accounts for the length of the detector loop. That is to say, the freeway vehicle is in the second sensor loop for a period of time equal to the time it takes to travel its own length plus the width of the sensor loop divided by the velocity of the vehicle as measured in the previous calculation.

The activity of the highway vehicle processor program represents a considerable fraction of the computing work load encountered by the green band system host computer, as will be evident from the discussion of the development of a simulation of this program, which will be reviewed in Chapter 5. The output of the HVP routine is a table of values for each freeway vehicle in the area upstream of the merge area monitored by the sensor stations associated with the system. Four pieces of information for each vehicle are stored as outlined above. The T1 value, the ETA at merge point value, the vehicle length, and the velocity of the vehicle for each up to nine vehicles are stored for each sensor station. Since there are seven freeway sensor stations, this represents a total storage in the table of 7 x 9 x 4 = 252 words of freeway vehicle information.

Data Logging Subprogram

This routine processed sensor data and system mode information into blockes of data for recording on a digital magnetic tape recorder supplied with the green band control system hardware. The resulting tapes were read and processed off-line for system performance evaluations. Operation of the data logging program was controlled by sense switches on the computer control panel.

The data logging program was called every 2 milliseconds after the input service subroutine had finished its duties. The data logging program read the four field sensor status words from the interface hardware and tested each word for changes. If any one bit or group of bits in a word had changed state, the entire four-word sensor block was stored in one of two 140 buffers in core. In addition, a time tag word was read from the timer value word in core and stored with the sensor status words. When the buffer currently being written into was full, it was written onto the tape by a tape recording subroutine. In the Woburn Green Band System, the data logging subprogram was modified from its Pacer counterpart to include data on system mode status and current green band speed with the other information recorded.

As mentioned above, a tape recording subroutine in the data logging subprogram accomplished the transfer of stored buffer data to the tape drive unit. In addition, after every fourth sensor change the status of the driver display lights was stored in a 15-word block in the tape output buffer by this section of the data logging program logic. The structure of the 140-word data buffer as recorded on tape was as shown in Figure 8.

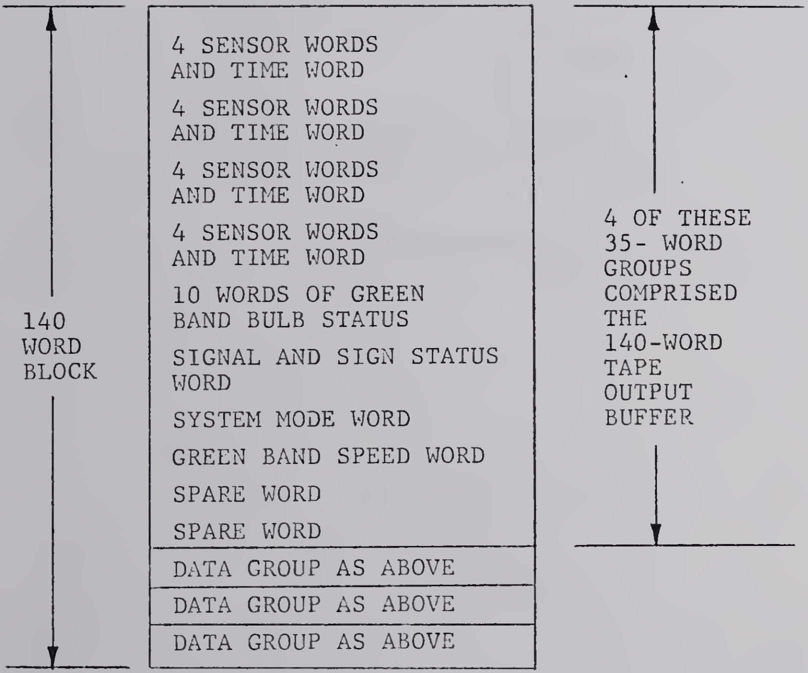


Figure 8. Data Logging Routine Tape Output Format for Woburn Green Band System

Green Band Status Routine:
Green Band Generation
(Woburn Constant Ramp Speed Case)

Green bands were generated by the Woburn System control program in the following manner. On each entry to the Green Band Status Routine (GBS), the highway vehicle sensor lists prepared by the HVP were checked to see if any highway vehicles with merge point ETA's greater than the most recent time of entrance to GBS were in the lists. If no such vehicles were found, the highway segment upstream of the ramp extending to the most distant sensor location was assumed to be free of traffic, and the entire length of the green band display was turned on to indicate the availability of a freeway "gap" whose length was at least as long as that of the display.

Assuming, however, that at least one vehicle was found in the sensor lists, a band was generated by taking the first vehicle expected at the merge point (the one whose ETA at merge was the smallest future time) and using this vehicle as the trailing highway vehicle for the first band on the display (the one nearest the downstream end). The leading edge of the band was set equal to the length of the display (640 feet for Woburn) and the trailing edge placment was found by the expression

$$XTE_{FIRST} = 892 - VMRG(ETA_T - TIME - THDY),$$

where 892 is the total distance from the start of the Woburn Green Band display to the merge point in feet, VMRG is the current green band speed in feet/second, ETA_T is the expected time of arrival of the freeway vehicle at the merge point in seconds, TIME is the current time in seconds, and THDY is a trailing headway allowance representing a safety factor (1.2 seconds was used for this value in Woburn). If the first freeway vehicle ETA was small with respect to the current time, the computed trailing edge of the associated band may have been off the end of the display. If this was in fact the case, the band was stored in a green band output table but was not displayed. The band speed for the first band was set equal to the current green band speed, VMRG. Green Band Status continued to search the highway sensor lists for pairs of leading and trailing vehicles. If any given vehicle ETA at merge was less than 0.25 seconds greater than the previous vehicle, the assumption was made that these data represented a downstream vehicle which had not yet been removed from the current sensor list, and the search continued with the next vehicle in the lists. If a vehicle with an arrival headway at least 2 seconds greater than the previous vehicle ETA was found, the measured gap between these vehicles was computed by the expression

$$MGAP = ETA_T - ETA_L - LENGTH_L,$$

where ETA_T and ETA_L represent the estimated merge point arrival times for the trailing and leading vehicles, respectively, and $LENGTH_L$ represents the length in seconds of the lead vehicle. The measured gap was tested against a "required gap," whose determination will be discussed in the next section and a decision to establish a band for the gap in question was made if the measured gap was greater than or equal to the required gap time for the two vehicles. If the decision was positive, the ith intermediate band to be displayed was created by setting

$$XLE_i = 892 - VMRG(ETA_L - TIME + LHDY + LENGTH_L),$$

$$XTE_i = XLE - (MGAP)(VMRG), \text{ and}$$

$$VBAND_i = \text{CURRENT GREEN BAND SPEED (VMRG)},$$

where LDHY is a leading headway allowance safety factor (0.4 seconds in Woburn). The process outlined in the discussion above was repeated until all pairs of freeway vehicles in the sensor lists had been processed.

When the last vehicle in the sensor lists was encountered, a band was created in the Green Band Table with the following parameters

$$XLE_{LAST} = 892 - VMRG(ETA_L - TIME + LHDY + LENGTH_L)$$

$$XTE_{LAST} = 0$$

$$VBAND_{LAST} = VMRG.$$

If the last vehicle had a large ETA at merge point with respect to the time of generation, the computed XLE value could have been negative, representing a band whose leading edge would not be on the physical display, and thus one which could not be displayed to the field.

Figure 9 shows the green band placements on the field display for the generation of the first band, intermediate band i, and the last band to be created in a given call to the GBS routine.

Green Band Status Routine

Determination of an Acceptable Freeway Gap Size for the Green Band Launch System

Since the major operational mission of a moving merge control system is to match ramp vehicles with available gaps in the freeway traffic stream, some method of classifying detected freeway gaps into the two mutually exclusive categories of those which will be used for an attempted merging maneuver and those which will not be used must be provided. One technique for performing this selection procedure is to consider the statistical properties of the gaps accepted and rejected by drivers at a given ramp, thus establishing a "critical gap," defined as the size of a gap in

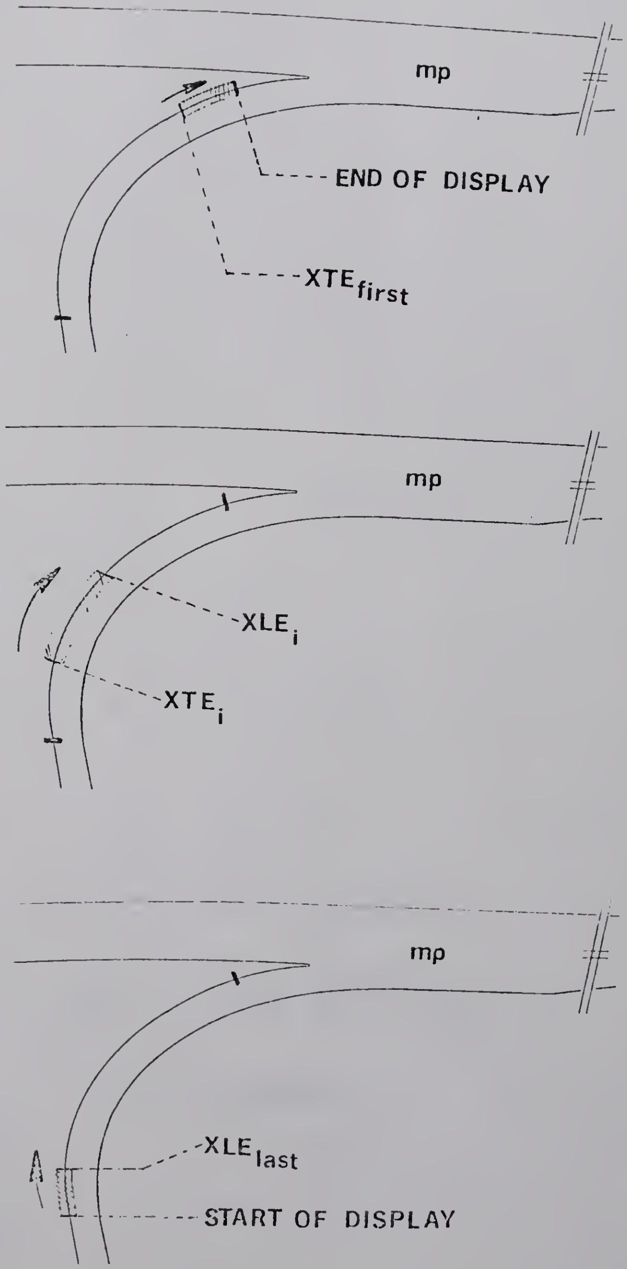


Figure 9. Green Band Display Element Parameter Definitions

time which will be accepted by 50% of the drivers using the ramp. Then, in the on-line control system, all measured freeway gaps smaller than this critical gap are rejected as unacceptable, and measured gaps greater than or equal to this value are used to program the ramp vehicles into a merging position. Typical values for the critical gap parameter at freeway entrance ramps are in the range of 2.0-4.0 seconds [44], and may vary with changing speed and flow conditions. Note that this critical gap value represents perhaps the most important dynamic ramp control system operating parameter, and its value should be carefully selected, as values which are too low will cause ramp vehicles to be projected into gaps which are too small for adequate vehicle separations, creating a potential safety hazard, and values for the gap acceptance parameter which are too high will cause unnecessary delay to be imparted to ramp vehicles while the control system is attempting to find gaps of the larger size on the freeway.

Another approach for classifiying freeway gaps into acceptable and unacceptable categories is to consider the relative trajectories in time and space of the vehicles involved in the merging process at the instant in time the gap is detected, and to use this information to compute a required gap to accomplish a safe merging operation for the vehicles involved (e.g., the ramp vehicle and the leading and trailing freeway vehicles defining the gap). Then, if the required gap to accomplish the merge with appropriate safety margins is less than or equal to the current measured gap on the freeway, the current gap becomes a candidate for use by the merge control system. If the required gap is greater than the measured gap, the current freeway gap is rejected by the merge control system and the search continues at the next detected gap. This latter appraoch was used by Raytheon in both the Pacer System and the Green Band System to evaluate freeway gaps for acceptability [83, pp. 4-108], and the implementation scheme used to carry out this procedure in the on-line system will be reviewed here to establish the framework of potential improvements to the Raytheon green band processing logic to be discussed later in Chapter 5.

The required freeway gap size for a ramp vehicle in the green band system is expressed as the sum of two terms:

$$\text{RGAP} = H_L + H_T,$$

where RGAP = Length of required gap (in seconds),

H_L = Required minimum time headway between ramp vehicle and leading vehicle of the freeway gap,

and H_T = Required minimum time headway between ramp vehicle and trailing vehicle of the highway gap.

The components of the required gap are computed in the following manner:

$$H_L = h_1 + h_1' + h_0$$

$$H_T = h_2 + h_2' + h_0 + L',$$

where h_1 and h_2 represent headway allowances based on the relative velocities of the highway vehicles defining the gap and the ramp vehicle,

h_1' and h_2' represent headway allowances to account for the errors in predicting freeway vehicle arrival times at the merge area based on point estimates of vehicle velocity taken upstream of the merge area,

h_0 represents a minimum acceptable freeway gap threshold time (0.8 seconds was used in Woburn),

and L' is the length of the ramp vehicle in seconds.

Recall that in the Pacer System, ramp vehicles were individually tracked by the on-line control program under a closed-loop control strategy. This supplied the control program with the values for length and velocity for each ramp vehicle identified as L' and V_R above. In the green band system, however, individual ramp vehicles are not tracked by the control system, and the gap calculations are performed using the current green band speed, VMRG, as the ramp vehicle velocity and a constant representing the value of the length (in time) of a vehicle 15 feet long is used for the length of the merging vehicle in the computations.

Define the following variables:

V_L = Velocity of leading freeway vehicle

V_T = Velocity of trailing freeway vehicle

VMRG = Current Green Band Velocity (assumed velocity of ramp vehicle)

d = Assumed vehicle deceleration = 4 feet/second^2

V_0 = Assumed velocity at which a vehicle has a zero acceleration capability = 146.7 feet/second

α = Acceleration capability of a vehicle moving at zero velocity = 5 feet/second.

Then, the equations for h_1 and h_2 as a function of freeway vehicle velocities and green band velocity are as shown in Table 1.

As indicated earlier, h_1' and h_2' represent additional gap requirements based on uncertainties in the measurement of freeway vehicle merge point arrival times due to upsteam velocity measurements. Raytheon estimated this error

TABLE 1

Calculations for h_1 and h_2 Components of Required Gap

$V_T > V_L$ FREEWAY GAP CLOSING	VMRG $> V_L$	$h_1 = (\text{VMRG} - V_L)^2/2dV_L$ $h_2 = (V_T - V_L)^2/2dV_L$	
	VL > VMRG	$h_1 = 0$ $h_2 = ((V_T - V_L)^2/2dV_L) + (V_0/\alpha V_L)[V_L - \text{VMRG} + (V_0 - V_L)(\text{LOG}_e((V_0 - V_L)/(V_0 - \text{VMRG}))]$	
$V_L > V_T$ FREEWAY GAP OPENING	VT > VMRG	$h_1 = 0$ $h_2 = (V_0/\alpha V_T)[V_T - \text{VMRG} + (V_0 - V_T)(\text{LOG}_e((V_0 - V_T)/(V_0 - V_R))]$	
	VMRG > VT	VMRG > VL	$h_1 = (\text{VMRG} - V_L)^2/2dV_L$ $h_2 = 0$
		$V_L >$ VMRG	$h_1 = 0$ $h_2 = 0$

at ±2% when the measurement was taken at the freeway detector station located 1,600 feet upstream of the assumed merge point [76, pp. 4-16].

Let ETA_L = Estimated time of arrival of leading freeway vehicle at the merge point,

ETA_T = Estimated time of arrival of trailing freeway vehicle at the merge point,

$TIME_L$ = Time of sensor report for leading vehicle when its ETA_L calculation was done,

and $TIME_T$ = Time of sensor report for trailing vehicle when its ETA_T calculation was done.

Then, the Raytheon expressions for freeway vehicle ETA measurement error correction factors were as follows:

$$h_1' = (0.777)(f_3(V_L))(ETA_L - TIME_L)$$

and

$$h_2' = (0.777)(f_3(V_T))(ETA_T - TIME_T),$$

where $f_3(V)$ is defined as:

$$f_3(V) = \begin{cases} 0.01, & V > 88 \text{ feet/second} \\ 0.01 + ((88 - V)/73.5), & 14.7 \text{ feet/second} \le V \le 88 \text{ feet/second} \\ 0.10, & V < 14.7 \text{ feet/second.} \end{cases}$$

This completes the mathematical specification of the components of the required gap computation equations.

Green Band Update Routine: Green Band Propagation Along Field Display

The appearance of motion of the bands of light on the field display representing acceptable freeway gaps is achieved in two ways. First, each time a band is created by Green Band Status (GBS), data representing its parameters (leading edge, trailing edge, current speed) are placed in a table of data which can store up to 15 bands. Another routine, Green Band Update (GBUD) is then called to update band positions and display them to the field hardware. Updating is done every 10 milliseconds, and consists of applying either

1) $DX = V(\Delta t)$ for a constant speed band,

or 2) $V = V_0 + a(\Delta t)$, and

$DX = V(\Delta t) + 1/2a(\Delta t)^2$, for an accelerating band,

to the stored parameters for all bands in the table before displaying them to the field.

The second factor at work to achieve band movement is the band generation process itself. At each entry to GBS, the green band table band count variable is cleared, effectively removing all current bands from the field display were the table to be displayed at that instant in time. This process occurs every 10 milliseconds, and continues with the creation of a new set of bands in the output tables. If new sensor data have been received since the last entry to GBS, new band positions will be generated for the gaps previously positioned on the field display during the last call, and similarly, as the band placement formulas use the variable TIME in the computations of leading and trailing edge placements, each call to GBS will result in new band positions even if the sensor data base has remained the same.

Thus, the two distinct processes of (1) band generation, and (2) band updating and display, work together to provide the apparent forward motion of the green bands along the display. The creation of a new band table every 10 milliseconds does allow the displayed bands to represent dynamically changing gap lengths on the freeway, but does give rise to certain band stability problems, which will be discussed in Chapter 5.

Situation Display Subprogram

This routine generated the control signals used to drive an operator display board in the control center for use with the ramp merge control systems. The board consisted of a row of light bulbs representing the upstream freeway outside lane traffic for both the green band and the Pacer systems, and rows of lights representing both the ramp vehicles and the pacer lights in the Pacer system, and only the green band display element in the Woburn Green Band System. As the green band system program did not use the ramp vehicle processing subprogram of the Pacer system, the situation display board control program did not have information available on the trajectories of ramp vehicles that could be used to drive display lights representing these vehicles.

Fault Monitor Subprogram

This routine was called to perform various computer arithmetic and sensor performance checks on the ramp control system hardware and to inform the operator via the teletype supplied with the system of potential error conditions. Only the 11 ramp sensors and 7 highway sensor stations in the Woburn installation were monitored. Fault tolerances (e.g., what percentage of vehicles out of a fixed number may be missed by a sensor before a warning is printed) were parameters in the control program which could be adjusted to give the required degree of system sensitivity to potential error conditions.

Green Band Velocity and Volume Program

This routine computed the average highway vehicle velocity at the first sensor upstream of the merge area in Woburn taken over a 3-minute averaging period, and computed the combined ramp and highway traffic volume taken downstream of the merging area across three freeway lanes. These two averages were updated every 10 milliseconds upon entry to the green band status program via a call to the velocity and volume subprogram if required due to sensor activations in the previous time interval. This routine operated on vehicle velocity data stored in core by the highway vehicle processing program and also directly accessed the sensors for the downstream volume computations by reading the data word containing the appropriate bit values from the input/output hardware interface.

The logic used to perform the velocity averaging over a three-minute period was somewhat unusual. A table of 600 words of core storage containing the velocities and times of sensor reports from freeway vehicle data was maintained. On each entry to the velocity volume subprogram, the table was searched for the vehicles included in the previous three-minute averaging period and the totals were accumulated based on a consideration of the results of the search. This approach of storing past data in a relatively large block of core indicated that core storage space was not a critical problem with the green band system as implemented in Woburn. Had this fact been a problem, the averaging procedures could have been accomplished through some form of exponential smoothing to alleviate the need for storing past data values.

Woburn Green Band System Mode Transition

Recall from the earlier discussions that the Woburn Green Band System had four possible operating modes. These were initialization, the stop metering mode (SM), the stopped-gap acceptance mode (SG), and the moving mode (MM). Also, as indicated earlier the system had an automatic capability for changing between these modes in response to evolving highway conditions. Figure 10 shows the basic changes between the three operating modes of SM, SG, and MM, and five additional mode transitions which were possible between the initialization state and the various operating modes. Figure 11 shows the green band system mode decision space which was used to establish the mode in which the system would be operating at a given point in time.

The basic control parameter for mode transition is the observed three-minute velocity average at the first upstream sensor. Values of V_1 and V_2 in Figure 11 represent the boundaries of a transition zone that existed between stop metering and stopped-gap modes of control. The transition from stop metering to stop gap requires that the velocity be greater than V_2. Similarly, the transition from stop gap to stop metering requires that the velocity be below V_1, which was set at 25 miles per hour, representing an expected condition of considerable freeway congestion. The

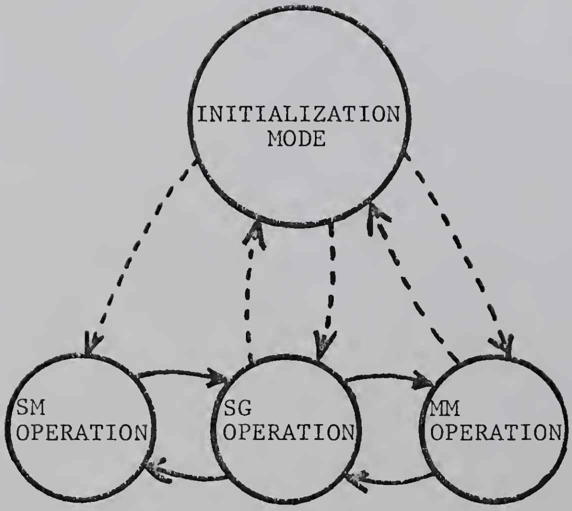


Figure 10. Possible Mode Transitions in the Woburn Green Band System

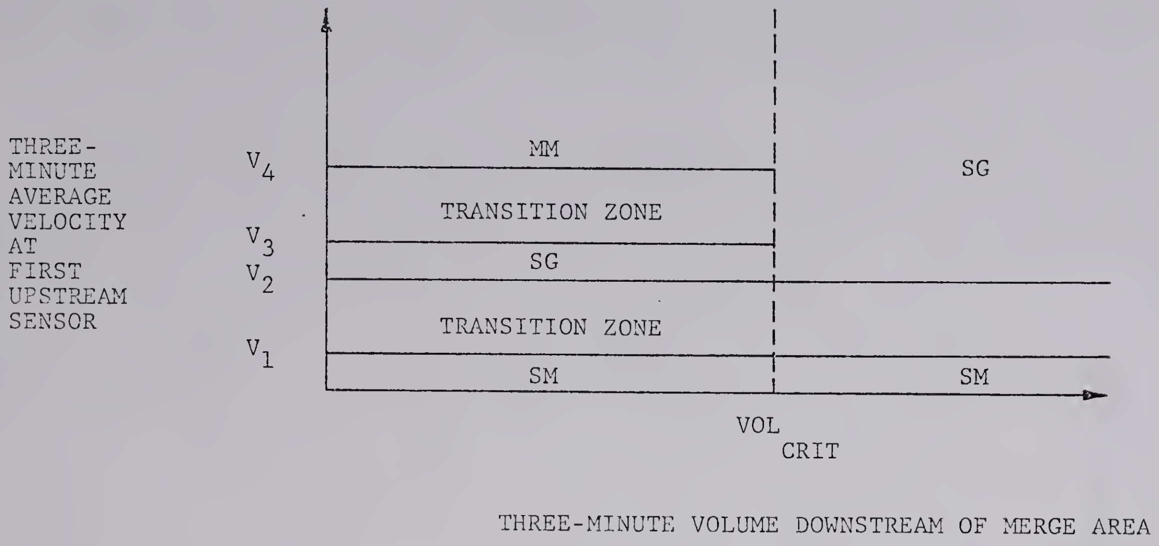

THREE-MINUTE AVERAGE VELOCITY AT FIRST UPSTREAM SENSOR
V_4
V_3
V_2
V_1
MM
TRANSITION ZONE
SG
TRANSITION ZONE
SM
SG
SM
VOL_{CRIT}
THREE-MINUTE VOLUME DOWNSTREAM OF MERGE AREA

Figure 11. Woburn Green Band System Mode Decision Space

horizontal area between V_1 and V_2 represented a transition zone which provided a hysterisis effect to reduce the possibility of frequent mode transitions if the freeway traffic is oscillating about some fixed speed point within this range. Similar transition zone allowances were used in the transitions to and from moving mode to stopped-gap. During the first three minutes of operation, the values for V_1, V_2, $V_3$and V_4 are respectively, 25, 28, 35, and 38 miles an hour. After the first three minutes of system operation these boundaries are changed to 25, 30, 35 and 40 miles per hour, respectively. Thus, the basic consideration in the choice of these values becomes the ability to predict the onset of freeway and/or ramp congestion, which would reduce the usefulness of the moving mode of operation of the system, by the use of real-time freeway velocity measurements.

Note the existence of a volume level in Figure 11. VOL_{CRIT}, which is also considered for mode control purposes. This figure represented a volume which, if reached downstream of the merge area, would cause the system to begin the transition from moving mode to stop gap. Although the capability for using this volume control as a mode switching parameter existed in the Woburn Green Band software, the value of the control parameter for volume switching was set to such a high limit that it would have had no effect on normal system operation (a comment in the control program listing indicates that this volume limit is such that it will never be reached [83, pp. 5-52]).

The dashed arrows in Figure 10 represent possible mode transitions between the initialization mode and the various operating modes. These are indicated to show that any of the three basic operating modes can be entered from the initialization routine when the sytem is started. Additional mode changes were possible to the initialization state in the Woburn System due to the fact that the two modes of stopped-gap acceptance and moving mode both used the green band update routine to move bands that had been generated down the ramp display, and when the Woburn green band update routine was being used, it monitored sensor occupancy in the merge area from the presence detectors installed in the acceleration lane, and had the capability of causing a system reinitialization if any one of the five merge area detectors were occupied for more than 30 seconds. After a 15-second reinitialization period, the initialization routine would then cause the system to enter one of the three basic traffic processing modes for the continuation of normal system activity. This latter action was done even if the presence area detectors were still occupied, thereby introducing the possibility that the system could exhibit behavior consisting of the display of bands or stopped-gap vehicle launching activity for a period of 30 seconds, then dropping back to initialization for 15 seconds, and continuing this cycle of 30 seconds of display and 15 seconds of initialization. This could have occurred in periods of high merge area occupancy such as might have been the case during periods of heavy ramp demands in the peak rush hour.

Another problem with the use of initialization as a system response to detected congestion in the merging area was the potential for having a system come out of initialization and begin generating green bands which would then direct vehicles on the ramp into vehicles possibly backed up from the merge area into the ramp display area. This would have represented a considerable safety hazard, but fortunately was not a problem in the Woburn system, as ramp congestion never became that severe.

Results of the Massachusetts Tests

The Woburn site tests of the dynamic moving merge control systems developed by Raytheon had the dual goal of (1) assessing the technical feasibility of such systems under actual field conditions, and (2) measuring the relative degree of public acceptance of the control system concepts. The successful public operation of both the Pacer and green band systems in the latter months of 1970 met the first goal, and results from a questionnaire handed to ramp vehicle drivers using the Woburn system indicated answers to the latter of the two objectives [86-88]. True and Rosen [87] reviewed the results of the Massachusetts tests with the following conclusions:

> Of those drivers using the pacer system, about 80% found it helpful, while 5% thought that it was difficult to follow the pacer lights. With the green band system, 85% considered it helpful and 8% considered it difficult to drive beside the green band. Because these responses involved several questions, the percentages do not add up to 100. Since many drivers used the test ramp repeatedly over a time period including both systems tests, it was possible to determine their preference between the two systems. Of the 210 drivers who used both systems and returned questionnaires, there was a general preference for the green band system.
>
> Based on responses from the questionnaires and the operation of a Pacer and green band systems in the Massachusetts tests, the following five statements can be made about moving merge control systems:
>
> 1. Moving merge control systems are technically feasible.
> 2. Approximately 80% of drivers feel such systems are beneficial.
> 3. Merging positions for ramp vehicles are improved.
> 4. Drivers prefer the somewhat simpler green band system which is also the more economical system.
> 5. The green band system deserves further field test evaluations.

The Tampa Green Band System Experiment

Based on the results cited above, the next step in the evolution of practical moving merge control systems was to install and evaluate the preferred green band system on a ramp which was experiencing serious operational merging problems, as opposed to the Woburn ramp, which was of good geometric design characteristics and was not considered to have been a severe enough test of the moving merge concept. Thus, a search was begun to identify a ramp where an evaluation could be performed to answer the basic question of "should a green band system be considered a viable alternative for improving the merging operations at a problem entrance ramp?" [87, p. 240]. To assist in the search for a problem ramp, the following list of test site requirements was developed:

1. The entrance ramp should be other than the clover leaf type with a restricted sight distance.
2. The length of the acceleration lane should be 400 feet or less.
3. The ramp to be used for a test subject should have a high accident experience rate with over 10 accidents yearly at the test location.

4. The ramp should have a relatively high off-peak merging volume with two well-defined peak periods of traffic daily. During these peak periods, ramp volume should be approximately 400 to 600 vehicles per hour, with a merging problem onto the freeway [89].

5. The minimum ramp length should be 500 feet.

6. The ramp should have a suitable area available on the left side of the entrance ramp for installation of the green band driver display elements.

7. There should be no upstream freeway on-ramp closer than 1,800 feet, or downstream off-ramp closer than 3,000 feet to the test ramp.

8. Test site should represent a ramp where reconstruction of the ramp facilities to eliminate the unsafe or capacity-reducing conditions would be too costly or impractical.

A number of states responded with candidate sites for the installation of the merge control system. After a thorough review of these locations by the Federal Highway Administration, the Ashley Street entrance ramp to I-75 in Tampa, Florida, was selected for the installation and evaluation of a green band moving merge control system under substandard merging conditions. Characteristics of the Ashley Street ramp with respect to the criteria mentioned above were as follows:

1. The ramp and freeway were both on elevated structures creating severe sight restrictions.

2. The acceleration lane was 318 feet in length, which is considerably shorter than current standards for entrance ramps to interstate highways.

3. The Ashley Street ramp had a considerable problem with accidents of the rear-end variety, with some 38 accidents of this category experienced in 1971 alone. Contributing to this accident potential was the high angle of convergence of the ramp of approximately 8 degrees with the freeway traffic stream.

4. The Ashley Street ramp had an average measured volume during the 4:00 P.M. to 6:00 P.M. weekday period of approximately 680 vehicles per hour, with severe queuing problems occurring on the ramp during these times.

5. The ramp length was 650 feet, entry point to nose.

6. There was an existing guard rail on the ramp structure available for green band display mounting.

7. The nearest on-ramp was 5,000 feet upstream, and the nearest off-ramp was 7,500 feet downstream from the Ashley ramp.

8. Since both the Ashley Street ramp and the freeway it serves are on elevated structures in downtown Tampa, geometric modification and reconstruction would have been extremely costly to implement.

In 1972, the University of Florida was awarded a contract by the State of Florida Department of Transportation to assist in the implementation of a merging control system on the Ashley Street ramp. A separate proposal was later prepared and submitted to cover the evaluation activities for the performance characteristics of the ramp. The system proposed for installation at the Ashley Street site was the green band system developed by Raytheon for the Federal Highway Administration and tested at the Woburn site. Contractual responsibilities of the University of Florida evolved from consulting on design characteristics of the system to preparation of software modifications to adapt the system to the Tampa site, and finally to the responsibility for implementing and testing the software modifications to get the system into operation. The nature of the hardware and software changes adopted to implement the Tampa system are discussed in Chapter 3, and research item components related to the evaluation of this system are discussed in Chapter 4.

CHAPTER 3
THE TAMPA GREEN BAND SYSTEM

Introduction

The departures from the earlier green band system as tested in Woburn used to install the Tampa system were of three basic categories [90-95]:

1. Changes which were required to describe the Tampa site geometry to the control program software, including information on sensor characteristics and locations and geometric limitations on the speed of ramp vehicles caused by a section with a radius of curvature of 230 feet in the middle of the Ashley Street ramp.

2. Corrections which were made to known and anticipated problems in the Woburn control algorithm, including revision of what were considered to be inappropriate system control responses to overtime occupancies of vehicles in the merge area acceleration lane.

3. Operating improvements representing additional capabilities over those provided in the Woburn Green Band System.

Each of the component elements of the Tampa Green Band System will be discussed individually in this chapter, including the ramp configuration, driver display design, sensor considerations, computer requirements, and green band control algorithm improvements.

The Tampa Ramp

The site selected for the installation of the Tampa Green Band Control System was the Ashley Street entrance ramp to I-75 in Tampa, Florida. This ramp provides a direct entrance to the freeway from the downtown Tampa central business district. The traffic volumes on the facility are moderate throughout the day, with a substantial peak occurring during the evening rush hour. The Average Daily Traffic (ADT) values for the eastbound roadway of the freeway are 38,000 vehicles per day and 7,000 vehicles per day for the ramp. Figures 12 and 13 show respectively data taken on January 24, 1974, representing five-minute volumes at the entrance to the Ashley Street ramp, and the sum of five-minute traffic volumes taken from sensors across the three freeway lanes

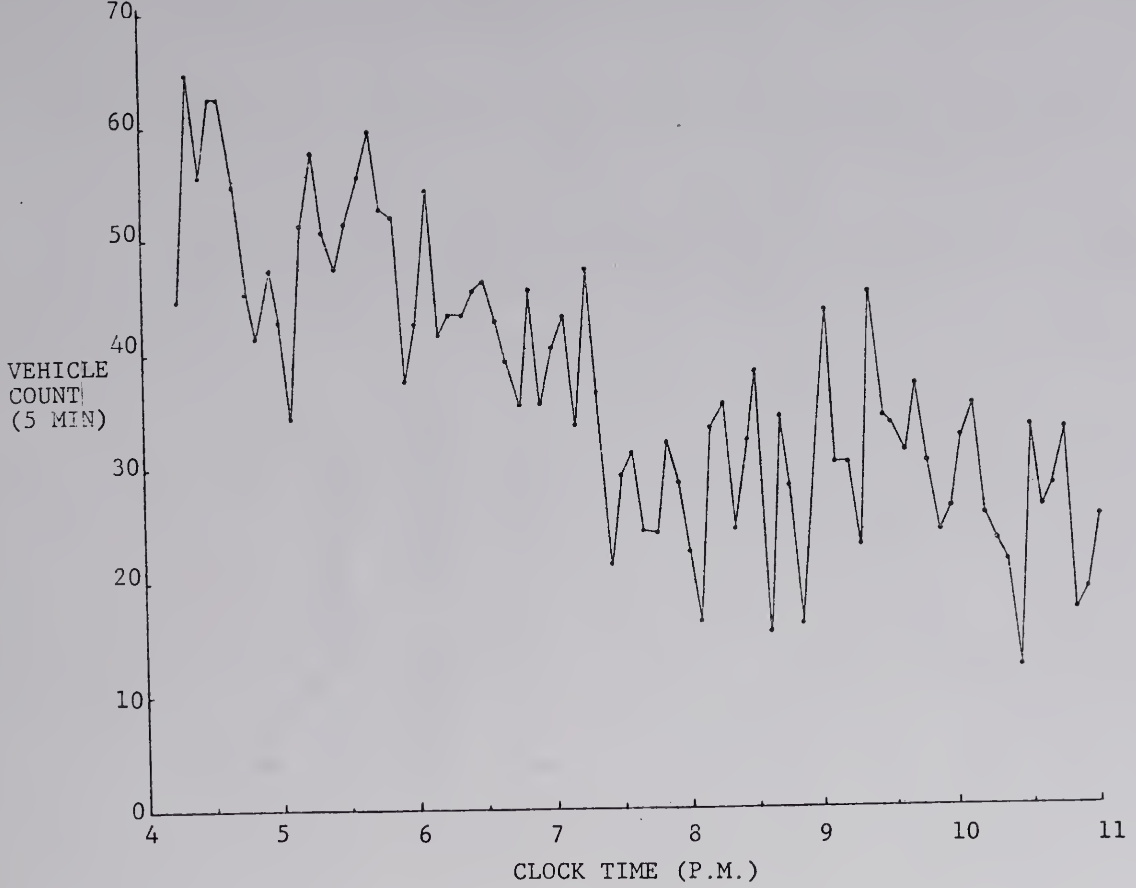


Figure 12. Five-Minute Volumes at Sensor R10 on January 24, 1974

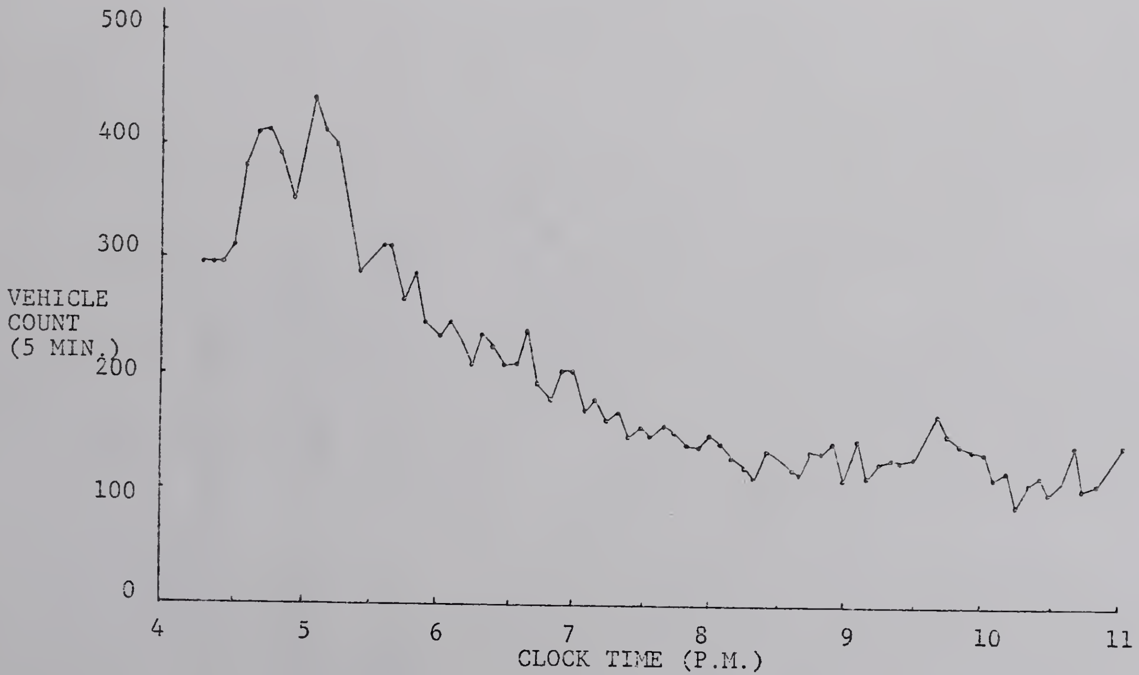


Figure 13. Five-Minute Volumes Across Sensors F1A, F1C, and F1E on January 24, 1974

downstream of the entrance ramp acceleration merge lane. Note the relatively high ramp demand during the 4:00 P.M. to 6:00 P.M. peak period, which is typical of week-day operation of the ramp. Data for these figures were produced by the computerized data collection system to be discussed later. Comparison of observed ramp volumes during peak demand periods with standardized expectations of ramp system capacity [89] indicated ramp operation at or above capacity, which was confirmed by the existence of long vehicle queues extending upstream of the ramp entrance during these times.

Sensor Installation at the Tampa Site

Figure 14 shows the instrumentation system used to monitor ramp and freeway vehicle activity in the Tampa Green Band System. The functions of the various sensors used in the on-line control program are as follows:

1. Double-loop sensors F7 through F1 supply information used to establish freeway vehicle trajectories upstream of the merge area. Sensor F1 is used to generate 3-minute freeway velocity averages for use in the system mode control logic.

2. Single-loop sensor R12 was originally installed to provide a capability for ramp

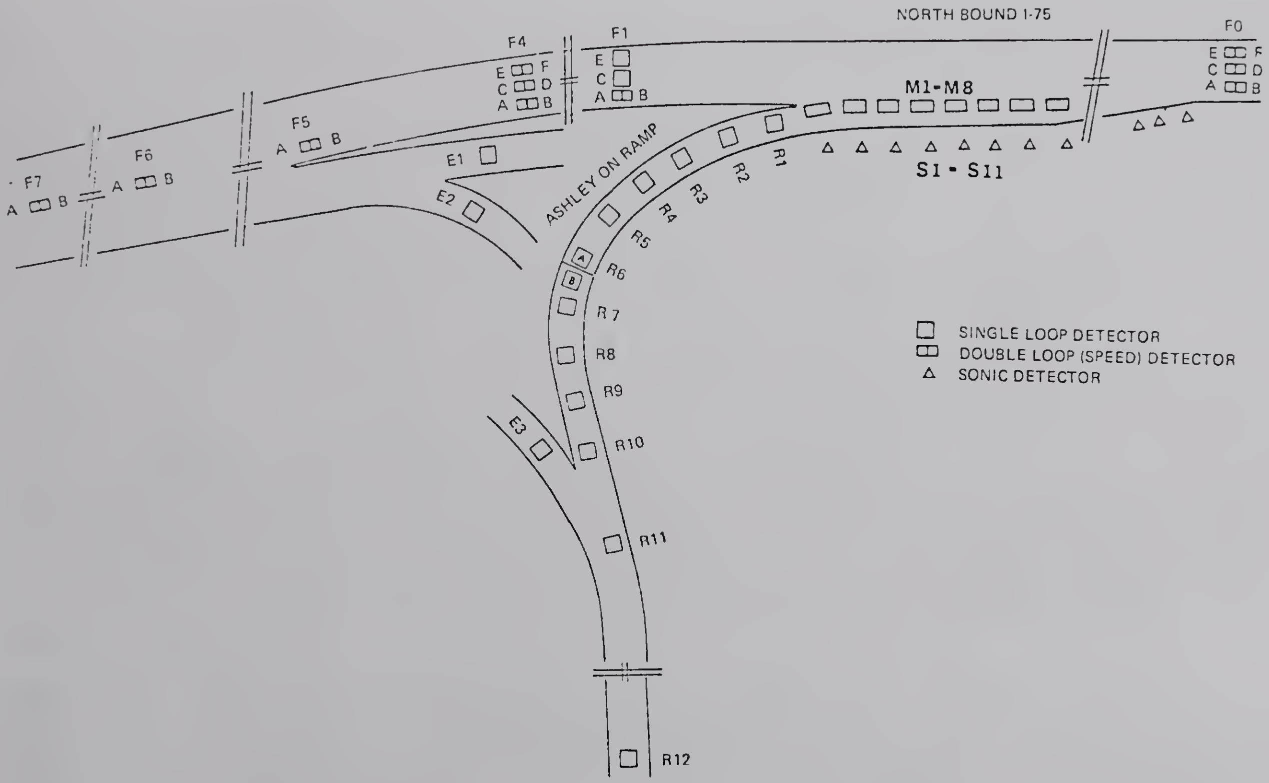


Figure 14. Tampa Moving Merge System: Instrumentation Subsystem

queue detection in the stopped modes of system operation. This function was later assigned to single-loop sensor R8 to allow a more rapid system response capability to the onset on ramp congestion.

3. Single loops denoted by R6B and R6A, respectively, serve as vehicle check-in and check-out detectors at the ramp traffic signal location in the stopped modes of system operation.

4. Single-loop sensor R3 is used to control the operation of a blank-out YIELD sign located at the end of the ramp display. This sign is illuminated if a ramp vehicle crosses R3 without an accompanying green band on the ramp display opposite this location.

5. Single-loop sensor F0A, which is the first loop of the double-loop freeway velocity sensor F0A/B, is used to generate continuous 3-minute counts of freeway and ramp merging volumes downstream of the acceleration lane.

This information is used by the system mode control logic in the Tampa software.

6. Acceleration lane presence sensors M1 through M8 are used to inhibit green band activity when occupied for a time greater than a preset threshold value.

The sensors above are the only detectors which are actually used by the on-line green band control program, and thus are representative of a minimum set of sensors required for green band system implementation at any ramp.

Additional sensors were used at the Tampa ramp for purposes of data collection for system performance evaluations, as will be discussed in Chapter 4. These additional sensors are scanned by the control program at the rate used for the on-line control sensors, and all field sensor activity is recorded on magnetic tape and processed in a manner to be discussed later. Additional sensors installed for evaluation purposes included double-loop sensors at freeway station F4 for monitoring center and inside freeway lane velocities, single-loop sensors at F1 for center lane and inside lane volume counts, double-loop sensors at station F0 for velocity profiles across the downstream freeway lanes, and single-loop sensors R11 through R1 extending throughout the length of the ramp to monitor merging vehicle trajectories. The Woburn Green Band System had double-loop velocity sensor stations on the ramp left over from the Pacer system implementation, but did not use these sensors in its control algorithm.

Additional sensors were installed on two off-ramps of I-75 in the study area and on the diversion to the south bound I-75 ramp extension on the Ashley ramp, represented in Figure 14 by sensors E1, E2, and E3, respectively. In addition, a series of eleven sonic detectors, modified electronically to report pulse widths proportional to vehicle spacings in front of the sensors, were installed on the guard rail of the acceleration lane and used to provide information on lateral vehicle displacements throughout the merging area. With the exception of the sonic detectors, all sensors were of the inductive loop type, positioned in grooves cut in the roadway surfaces and covered with a heavy-duty sealant compound [95, p. A.15]. Sensor data were transmitted over hard-wired communication lines specifically installed for this purpose.

Driver Display Configuration

The Woburn Green Band System driver display consisted of a series of 156 display elements, each four feet in length and containing two 75-watt flood lamps wired in parallel, and covered with a sheet of green acrylic plastic. Thus, the display in operation had the appearance of a series of moving points of green light representing the bands displayed by the system. In addition, the other display elements as reviewed in Figure 4, Chapter 2, consisted of a changeable message speed sign representing one of three different speed levels for current band speed, a standard three-face traffic signal positioned approximately one-third of the way along the display, a fixed message sign indicating "Drive Beside Green Band," and a sign at the end of the display element indicating a "Merge With Caution" indication which could be illuminated when the system was unable to find a green band for the current ramp vehicle.

Consideration was given to the Woburn display in the design of the Tampa system elements and the final configuration implemented is shown in Figures 15 and 16. The green band display consists of a series of 152 green fluorescent light bulbs, each four feet long, housed in 76 aluminum channel sections placed end to end on the left-hand side of the guard rail, and covered with sheets of clear plastic. The final configuration of this display element was determined by consideration of anticipated display visibility under varying conditions of ambient illumination, and it was felt that the appearance of continuous linear bands on the display rather than the band composition scheme used in the

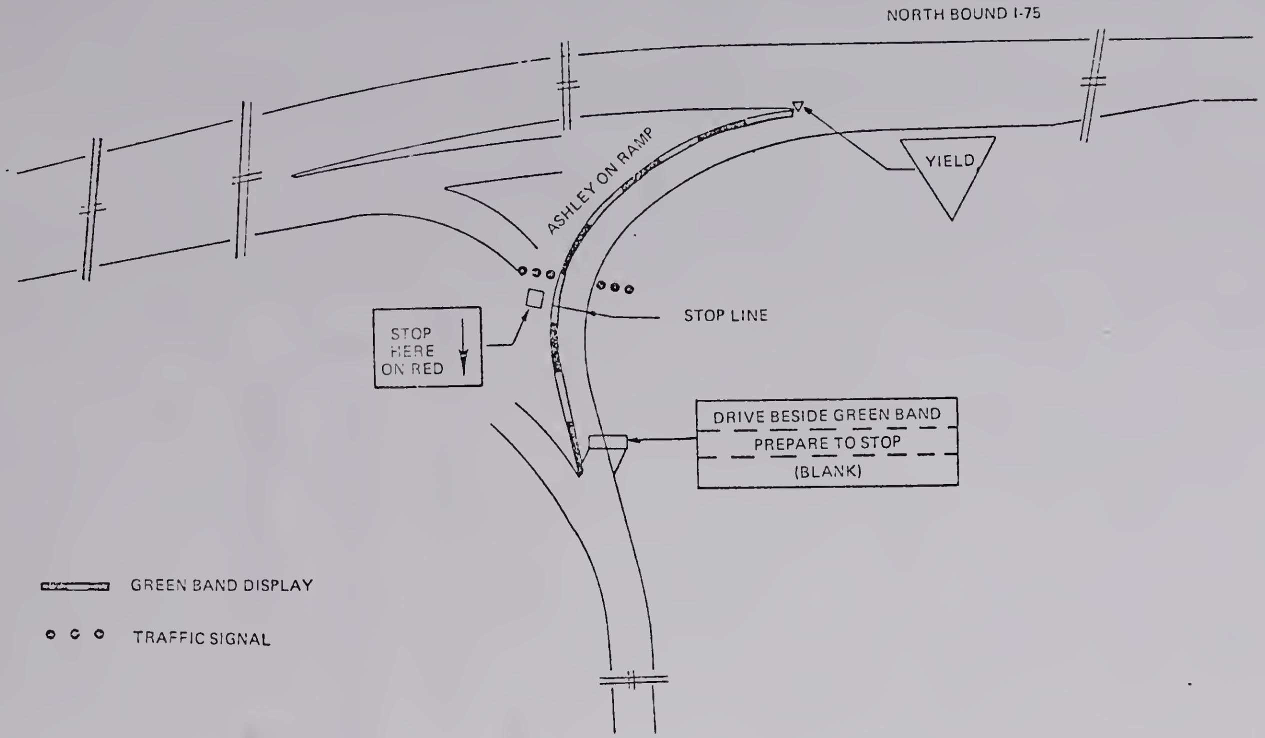


Figure 15. Tampa Moving Merge System: Driver Display Subsystem

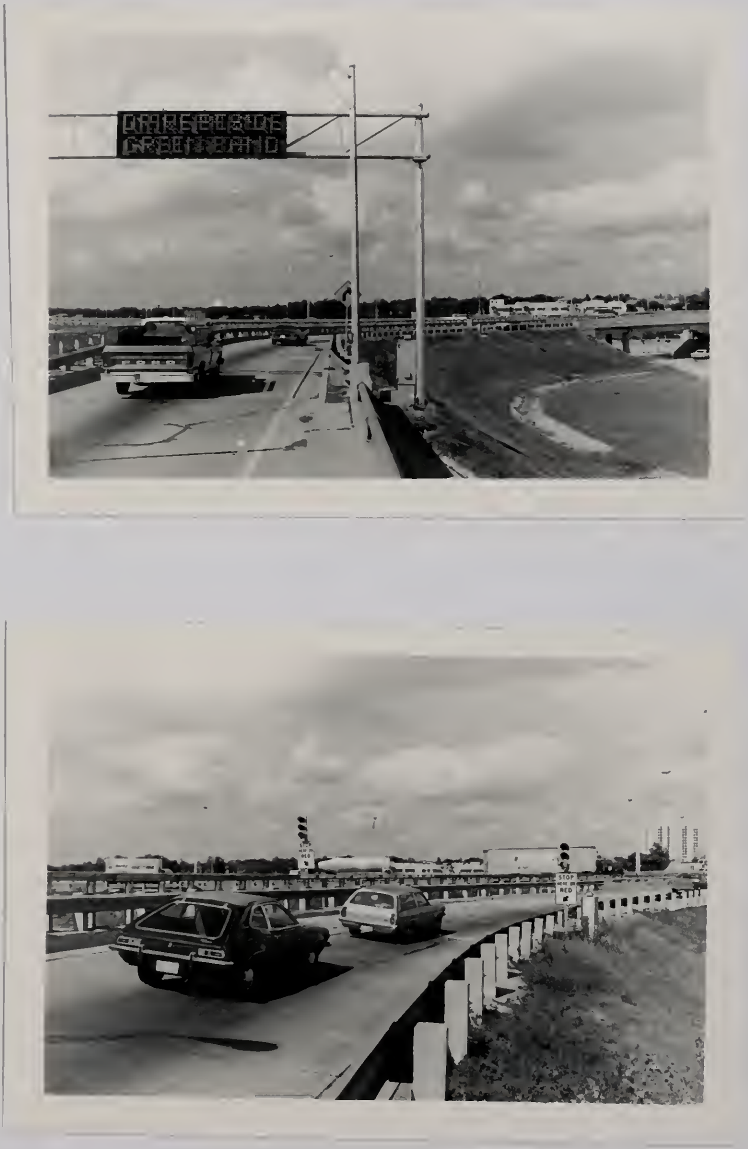


Figure 16. The Elements of the Driver Display in the Tampa Green Band System

Woburn system would provide a more effective target for ramp vehicles to follow. Special "instant-on" fluorescent light ballasts were required to achieve the capability for the frequency of lamp switching required by the control program [85].

The use of a changeable speed sign to indicate to ramp drivers the velocity of the current green bands was considered and rejected, as the Tampa Green Band System had to be designed to generate green bands moving at fixed speeds throughout the initial section of the ramp and accelerating to a final merge velocity once the section of the ramp where the maximum safe speed was 30 mph had been passed. To provide the ramp driver with information on the current mode of the system, a changeable-message matrix sign was installed on an overhead support at the beginning of the ramp as shown in Figure 15. The sign displays the message DRIVE BESIDE GREEN BAND when the system is in the moving mode and the message PREPARE TO STOP when the system is in either the stopped-gap acceptance or stopped metering modes. To accomplish the vehicle stopping function in the latter two modes, two standard three-face traffic signals were installed at the stop line location on either side of the ramp. The sign indicating MERGE WITH CAUTION in the Woburn Green Band System was replaced with a blank-out YIELD sign located at the end of the ramp display, as it was felt that this sign would give a more positive indication to the ramp drivers of the existence of potentially hazardous merging situations than would have the other sign. Control lines to the various elements of the driver display were run from the system control center, located in the City of Tampa Traffic Control Center Building immediately adjacent to the ramp. Electrical isolation and lightning protection facilities for the component elements of the sensor installation and for the driver display were provided [94, 95].

Computer Facilities for the Tampa Green Band Syatem

A Raytheon Model 704 computer is used as the control element for the Tampa Green Band System [90, 91]. This machine is a later version of the Raytheon Model 703 computer used in the Woburn Green Band System, with the same instruction set and a basic instruction cycle time of 1.0 microseconds, as compared to a cycle time value of 1.75 microseconds for its predecessor. The machine has a core memory of 16,000 16-bit words, representing an increase of 4,000 words over that used in the Woburn system. The additional memory space is used for data buffers for the on-line data recording scheme, and does not represent a need for additional core requirements by the Tampa control program. Sensor inputs from the field are processed by a special-purpose output hardware interface, which also contains a hardware clock which operates at a cycle time of two milliseconds to provide an accurate time base for the operation of the system. Control instructions issued by the computer are sent to the field through hardware called the storage control unit, which consists of data buffers between the computer output lines and the various elements of the driver display. A high-speed paper tape reader is included with the system for program loading, and a high-speed paper punch is used for program preparation and editing. A Model ASR-35 Teletype Unit is used to provide a capability for receiving on-line status messages from the control system and transmitting operator control inputs and data logging messages to the system. A nine-channel IBM-compatible magnetic tape unit is used to record data on sensor activations and control program outputs during on-line operation. A photograph of the control element appears in Figure 17, which also shows the situation display board, which is positioned over the racks containing the computer equipment. The display board lamp arrangement was not modified from the Woburn configuration to reflect the different geometry associated with the Tampa ramp.

Table 2 shows the interrupt level and input/output channel assignments for the Woburn and Tampa control computers. The magnetic tape function interrupt activity was

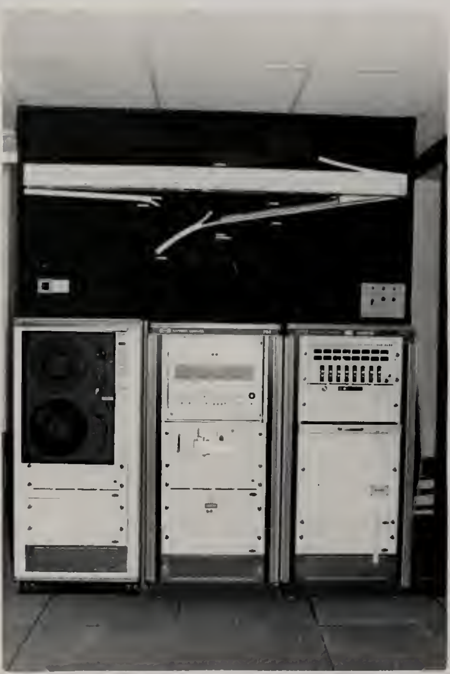


Figure 17. Control Equipment Hardware for the Tampa Green Band System

Table 2
Interrupt Level and Input/Output Channel Assignments
for the Woburn and Tampa Green Band System Control Computers

INTERRUPT LEVEL ASSIGNMENTS

INCREASING PRIORITY ↓

LEVEL #	WOBURN USE	TAMPA USE
0	MAG TAPE FUNCTION, TELETYPE	TELETYPE, PAPER TAPE READER AND PUNCH
1	FAULT MONITOR	OPERATOR RE-INITIALIZE BUTTON
2	CLOCK	MAG TAPE FUNCTION
3	MAGNETIC TAPE DATA CONTROL	NOT USED
4	NOT AVAILABLE IN HARDWARE	CLOCK
5	NOT AVAILABLE IN HARDWARE	MAG TAPE DATA CONTROL
6	NOT AVAILABLE IN HARDWARE	FAULT MONITOR
7	NOT AVAILABLE IN HARDWARE	POWER FAIL

INPUT/OUTPUT CHANNELS

CHANNEL #	
0	DRIVER DISPLAY COMMANDS TO FIELD
4	COMMUNICATION WITH FAULT MONITOR HARDWARE
8	SITUATION DISPLAY BOARD DATA
9	MAGNETIC TAPE DATA AND CONTROL
12	PAPER TAPE PUNCH DATA AND CONTROL
13	PAPER TAPE READER DATA AND CONTROL
14	TELETYPE DATA AND CONTROL
15	FIELD SENSOR INPUTS

isolated from its common assignment to level 0 with the teletype in the Woburn system to prevent the possibility of interference between tape recording operations and teletype usage. The interrupt priority level for the clock pulses was raised to insure adequate isolation of this function from the other system activity, and the fault monitoring interrupt level was placed at a priority level just below that of the power fail interrupt servicing to insure the capability for the automatic shut-down of the system if error conditions have been detected.

Situation Display Board Modifications

The situation display subroutine of the on-line green band system provides vehicle and driver display (e.g., green band position) information to operate the situation display board. The situation display control software from Woburn was modified to reflect the positions of the Tampa freeway sensors on the highway to accurately represent the update intervals of vehicles passing through the upstream section of the freeway. In addition, a capability for displaying field sensor actuations in real-time while the green band system is running was added to the situation display control program. This option can be selected by using a thumb wheel control switch on the front panel of the situation display. The operation of the field sensor monitor capability is simply to read the status of the four input words containing the field sensor data and then to display this information on a set of 61 bulbs which were added to the face of the display. As long as a sensor is reporting an on condition from the field, the corresponding bulb on the situation display board located approximately at the correct geometrical position of the sensor in the field on the board is also on. As the field sensor goes off, the corresponding bulb goes off. This capability provides an effective tool for monitoring the performance of field sensors, as vehicles can be tracked by monitoring their progress on the board through the various sensor sequences. The ability to detect malfunctioning sensors in this fashion has proven to be a valuable operating feature of the system, as the Tampa area experiences a much higher than normal rate of electrical storm activity compared to much of the rest of the country, and considerable difficulty has been experienced in keeping the sensors operating properly for use in the green band system. A section was included in the Tampa Green Band System Operator Manual [94] which recommends the use of this mode of display board operation each morning before turning the system on for the public to monitor the proper functioning of all sensors associated with the system. This has been implemented as a daily practice and has proven to be an effective means of scheduling maintenance activities for the system when needed.

Operator Communication with the On-Line Control Program in the Tampa Green Band System

The operator monitor subprogram of the Woburn Green Band System did not work properly, according to Mr. A. R. Thayer of the Raytheon Corporation [personal communication]. An addressing problem prevented the transfer of data to the system and did not allow the full capabilities for this routine discussed in the operating manuals for the Pacer and green band systems to be used reliably in practice [77]. Raytheon suggested a number of changes to the original Woburn software to correct these problems, and the Tampa Green Band System now has an operating capability for operator communication with the control system while the system is running using the teletype unit. Provisions in the control software enable the operator to selectively inspect single core locations in the memory of the machine, or groups of core locations, and to change values in core while the program is running. This allows experimentation with parameter values in the operating system without the need for shutting down the system to make such changes. In addition, software modifications were designed and implemented locally to provide several additional features for monitoring system operation from the teletype console. Included in these are a capability for the system to print the source of system generated reinitializations, which can be caused by such factors as arithmetic errors in calculations made by the green band status routine, for example. Also, logic was added to service an operator reinitialization button located on the teletype console. This generates an interruption to the control system on a priority level which inhibits the display of driver control information to the field and places the stop light on the ramp in a flashing amber mode for a period of 15 seconds, allowing the operator to shut down the system quickly without having to walk to the computer console should unexpected trouble develop. To provide an additional research capability for manually monitoring the operations of the system, provisions were made in the operator monitor software logic to print the time and nature of each system mode change commanded by the on-line program during the day and also to print the time of each band masking and unmasking condition when this activity occurs. This gives the operator a capability for monitoring field operations without the need for using the television system provided with the experimental control system.

Hardware Fail-Safe Capabilities of the Tampa Green Band System

The Raytheon 703 computer used in the Woburn Green Band System had four hardware interrupt levels which did not include the optional power fail-safe hardware [91]. The Raytheon 704 computer used in the Tampa system was ordered with eight interrupt levels and the power fail-safe option which is factory-installed on the highest interrupt level. Coding was devised to service this hardware and a capability for the automatic monitoring of the input power supplied to the green band control system was implemented. This provides a means for a safe and orderly automatic shutdown in the event of a power failure, leaving the field display in a safe condition (e.g., no bands and flashing amber if the field power remains on). The routine also has a capability for operator notification and automatic system reinitialization when the power is restored. The system hardware supplied with the Tampa system did not have satisfactory fault monitoring circuitry and new circuitry was designed to improve this capability. The function of this hardware is to monitor responses to the clock pulses used to generate the interrupts which provide the basic cycle timing for the green band control system. Each time a clock interrupt is serviced, an output instruction to the fault monitor hardware is issued which resets a hardware timer whose period is longer than the expected time until the next clock update, four milliseconds, and two milliseconds, respectively. If this time should ever reach a zero condition, an interrupt is automatically generated, causing the system to notify the operator of a potential clock fault in the hardware and then to automatically shut itself down. This capability prevents the computer from "looping" in a subroutine in response to unexpected data conditions or hardware failures.

Tampa Green Band System Mode Change Logic Revisions

As indicated earlier in Chapter 2, the Woburn Green Band System had a capability for using the three-minute freeway volume (computed by the on-line control system from detectors downstream of the ramp and extending across the freeway) to inhibit mode changes from stopped-gap operation to moving mode, and to force mode changes from a moving mode operation to stopped-gap operation when a single predetermined volume level was reached or exceeded. This volume-based mode control logic was structured to operate only after the system had been running at least three minutes to minimize the possibility of transient mode change effects in the early operation while the first three-minute volume average was being initialized. Examination of control program listings supplied by Raytheon revealed that this volume switching constant (the variable QLIMIT in the Green Band Status Routine [83, pp. 5-52]) had been set to a value representing an hourly freeway volume across three lanes of 10,240 vehicles per hour. This was clearly above what would ever be observed under actual conditions on a three-lane freeway, and, therefore, using this variable value had the net effect of disabling the volume switching logic. With this capability disabled, system mode changes in Woburn were made strictly on the basis of a three-minute freeway velocity average from the freeway right-hand lane taken just upstream of the entrance ramp at sensor station K-30 (corresponding to sensor F1 in the Tampa system). The original Woburn mode switching logic was used in Tampa for initial system experimentation and was found to cause problems in the public operation of the system, as the Tampa freeway speeds remained high enough during peak hour conditions to keep the system in moving mode, while the ramp vehicles were experiencing problems in accomplishing the moving merge maneuvers associated with this mode of operation. Thus, some technique was needed other than strict velocity switching logic to force the system into the stopped-gap mode of operation during periods when ramp congestion was highly probable and freeway velocity values remained high.

To implement such a technique several program changes were made. First, the volume reporting logic was modified to consider only the right-hand lane freeway volume downstream of the ramp instead of considering the total freeway volume across the three lanes of traffic used in the Woburn software. As ramp traffic interacts most strongly with this outside freeway lane, it was felt that the specific volume here would serve as a better control parameter than the total freeway volume. Secondly, two different boundary conditions using volume as a switching parameter were implemented for use in the mode transition logic to provide a hysterisis effect similar to that used in velocity-based mode transitions to minimize transient conditions in operational mode switching. Figure 18 shows the current mode control algorithm implemented in Tampa. Experimentation is needed for future system refinements to determine sufficiently accurate prediction criteria for ramp congestion based on measured freeway volume and velocity data, and special features were added to the data logging routine for the Tampa system to record continuous information on the volume and velocity averages for the freeway being used in the current on-line switching logic. This data can be used in conjunction with the standard mode status output generated by the data logging system to correlate system mode switching behavior with measured variable values on the freeway and ramp.

Tampa System Response to Merge Area Congestion

The Woburn Green Band System had a series of five presence detector loops located in the merge area acceleration lane and connected to the control computer. These loops were monitored by the control software and software flags were set each time any one of the five loops was activated. If any one of these detectors had been activated for more than 30 seconds, the on-line system automatically went to a routine which began the initialization phase for the on-

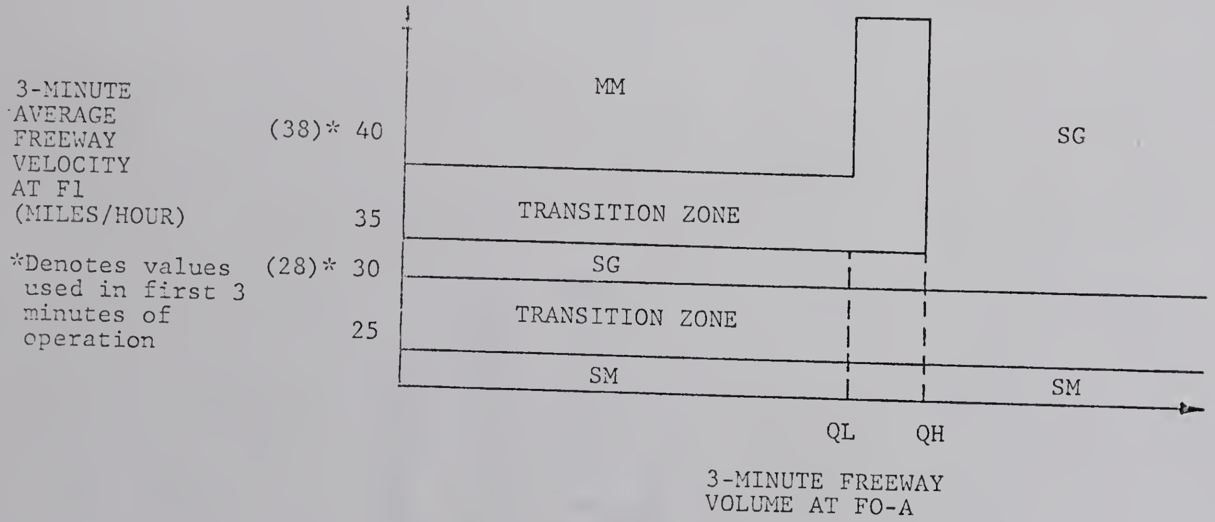

3-MINUTE AVERAGE FREEWAY VELOCITY AT F1 (MILES/HOUR)
*Denotes values used in first 3 minutes of operation
(38)* 40
35
(28)* 30
25
MM
TRANSITION ZONE
SG
TRANSITION ZONE
SM
SG
SM
QL
QH
3-MINUTE FREEWAY VOLUME AT FO-A

Figure 18. Mode Change Currently Implemented for the Tampa Green Band System

line control software. This consisted of a period of 15 seconds of time in which no green bands were displayed and the ramp traffic signal was controlled to a flashing amber indication.

This response was not found to be sufficiently sensitive to timely determination of the onset of ramp congestion and the control algorithm was modified for use in the Tampa system. The Tampa system uses eight presence loop detectors in the merge area, respectively M1 through M8, and monitors each of these loops continually while the program is in operation. If any one of the eight loops becomes occupied for more than five consecutive seconds, the system "masks" the display of green band information to the field. The system activities of freeway vehicle tracking and band generation continue, but the resulting green bands are not displayed to the field again until all of the eight presence detectors are clear. The primary operational benefit of this concept is the removal of the possibility of the system directing ramp vehicles into the rear of other ramp vehicles stopped in at the merge area by providing them with a moving green band. An important ancillary benefit associated with band masking rather than system reinitialization is the reduction in time spent in system initialization, which served to reduce the time the system was actually benefiting ramp vehicle traffic in the Woburn system.

The band masking time threshold parameter of five seconds was determined by visual observation of the operations of the system from the roof of the control center overlooking the ramp and merge area. It was determined that the value used in the Woburn system for system response to congestion of 30 seconds was much too high to represent an effective safety measure for the Tampa ramp traffic conditions. The time value of five seconds gives sufficient time for slow moving ramp vehicles to clear each detector without activating the masking process, and yet is short enough to detect a stopped vehicle condition in time to delete a green band from the display before potentially troublesome situations can develop.

Stopped-Gap Mode Band Acceleration Profiles for the Tampa Green Band System

The Woburn Green Band System control program was based on the assumption that vehicles in the stopped-gap mode of operation would leave the stop line after a green indication at an average acceleration of four feet per second^2 and would continue at this acceleration to the final projected band speed, VMRG, and this acceleration value was used in the control program for band propagation in the stopped-gap mode. Tignor [88] showed that the use of this value resulted in many ramp vehicles in the Woburn system not being able to successfully follow the bands in the latter portions of the ramp in the stopped-gap mode. He suggested the use of a variable acceleration rate representing more accurately the acceleration capabilities of typical ramp vehicles from a standing start.

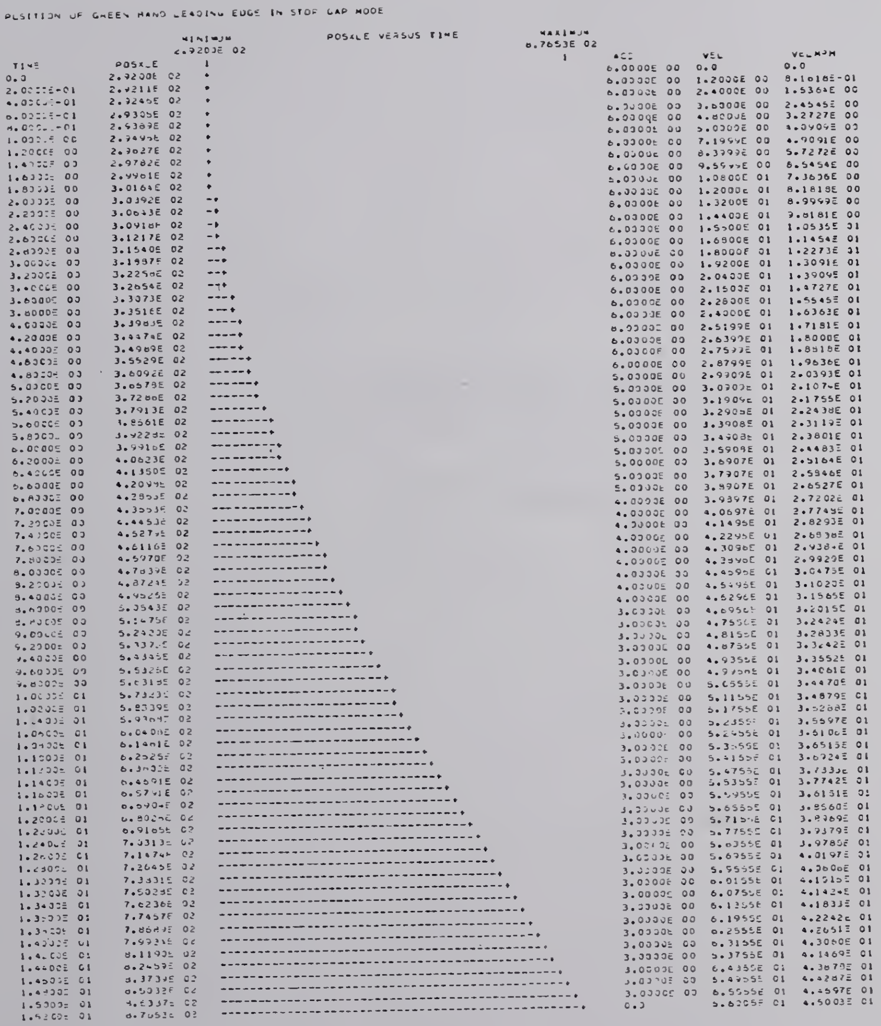
To investigate the feasibility of this approach and to provide estimated times of arrival of ramp vehicles at the merge point under variable acceleration profiles, an IBM System/360 CSMP computer program was devised to study this problem. Figure 19 shows the program and Figure 20 shows a computer-generated plot of green band edge position in the stopped-gap mode with the variable acceleration profile currently implemented in the Tampa control system. The final scheme was to use an initial acceleration rate away from the stop line of six feet per second^2 for controlling the the band movement, which was two feet per second^2 higher than the corresponding Woburn value. As the band speed and corresponding ramp vehicle speed increase, the acceleration of the band is reduced first to five feet per second^2 when the vehicle speed has reached approximately 28 feet per second, and then to four feet per second^2 when the vehicle speed is 39 feet per second, and finally to three feet per second^2 acceleration when the vehicle speed has reached 46.9 feet per second. This acceleration profile closely matches actual observed vehicle performance in accelerating from

```
                ****CONTINUOUS SYSTEM MODELING PROGRAM****

         ***PROBLEM INPUT STATEMENTS***

 *
 TITLE TAMPA SG BAND ETA PREDICTION PGM
 INITIAL
          RMPL = 844.
          XTEIC = 260.
          XLEIC = 292.
          FPSMPH = 88./60.
          VMRG = 66.
 DYNAMIC
 NOSORT
          ACC = 3.0
          IF(POSXLE.LT.508.)  ACC = 4.0
          IF(POSXLE.LT.430.)  ACC = 5.0
          IF(POSXLE.LT.364.)  ACC = 6.0
          IF(VEL.GE.VMRG)     ACC = 0.0
 SORT
          VEL = INTGRL(0.0.ACC)
          POSXLE = INTGRL(XLEIC,VEL)
          POSXTE = INTGRL(XTEIC,VEL)
          VELMPH = VEL/FPSMPH
 TIMER PRDEL=.20,FINTIM=100.,DELT=.01,OUTDEL=.20
 PRTPLOT POSXLE(ACC,VEL,VELMPH)
 LABEL POSITION OF GREEN BAND LEADING EDGE IN STOP GAP MODE
 FINISH POSXTE=RMPL
 METHOD RECT
 END
 STOP
```

Figure 19. IBM System/360 CSMP Program for the Analysis of Green Band Trajectories Under Variable Acceleration Profiles in the Stopped-Gap Operating Mode



```
POSITION OF GREEN BAND LEADING EDGE IN STOP GAP MODE

                                  MINIMUM          POSXLE VERSUS TIME           MAXIMUM
                                  2.9200E 02                                    8.7653E 02
 TIME           POSXLE            I                                             I        ACC          VEL          VELMPH
0.0             2.9200E 02                                                               6.0000E 00   0.0          0.0
2.0000E-01      2.9211E 02                                                               6.0000E 00   1.2000E 00   8.1818E-01
4.0000E-01      2.9246E 02                                                               6.0000E 00   2.4000E 00   1.6364E 00
6.0000E-01      2.9305E 02                                                               6.0000E 00   3.6000E 00   2.4545E 00
8.0000E-01      2.9389E 02                                                               6.0000E 00   4.8000E 00   3.2727E 00
1.0000E 00      2.9496E 02                                                               6.0000E 00   6.0000E 00   4.0909E 00
1.2000E 00      2.9627E 02                                                               6.0000E 00   7.1999E 00   4.9091E 00
1.4000E 00      2.9782E 02                                                               6.0000E 00   8.3999E 00   5.7272E 00
1.6000E 00      2.9961E 02                                                               6.0000E 00   9.5999E 00   6.5454E 00
1.8000E 00      3.0164E 02                                                               6.0000E 00   1.0800E 01   7.3636E 00
2.0000E 00      3.0392E 02                                                               6.0000E 00   1.2000E 01   8.1818E 00
2.2000E 00      3.0643E 02                                                               6.0000E 00   1.3200E 01   8.9999E 00
2.4000E 00      3.0918E 02                                                               6.0000E 00   1.4400E 01   9.8181E 00
2.6000E 00      3.1217E 02                                                               6.0000E 00   1.5600E 01   1.0636E 01
2.8000E 00      3.1540E 02                                                               6.0000E 00   1.6800E 01   1.1454E 01
3.0000E 00      3.1887E 02                                                               6.0000E 00   1.8000E 01   1.2273E 01
3.2000E 00      3.2258E 02                                                               6.0000E 00   1.9200E 01   1.3091E 01
3.4000E 00      3.2654E 02                                                               6.0000E 00   2.0400E 01   1.3909E 01
3.6000E 00      3.3073E 02                                                               6.0000E 00   2.1600E 01   1.4727E 01
3.8000E 00      3.3516E 02                                                               6.0000E 00   2.2800E 01   1.5545E 01
4.0000E 00      3.3983E 02                                                               6.0000E 00   2.4000E 01   1.6363E 01
4.2000E 00      3.4474E 02                                                               6.0000E 00   2.5199E 01   1.7181E 01
4.4000E 00      3.4989E 02                                                               6.0000E 00   2.6399E 01   1.8000E 01
4.6000E 00      3.5529E 02                                                               6.0000E 00   2.7599E 01   1.8818E 01
4.8000E 00      3.6092E 02                                                               6.0000E 00   2.8799E 01   1.9636E 01
5.0000E 00      3.6678E 02                                                               5.0000E 00   2.9909E 01   2.0393E 01
5.2000E 00      3.7286E 02                                                               5.0000E 00   3.0909E 01   2.1074E 01
5.4000E 00      3.7913E 02                                                               5.0000E 00   3.1909E 01   2.1755E 01
5.6000E 00      3.8561E 02                                                               5.0000E 00   3.2909E 01   2.2438E 01
5.8000E 00      3.9228E 02                                                               5.0000E 00   3.3908E 01   2.3119E 01
6.0000E 00      3.9916E 02                                                               5.0000E 00   3.4908E 01   2.3801E 01
6.2000E 00      4.0623E 02                                                               5.0000E 00   3.5909E 01   2.4483E 01
6.4000E 00      4.1350E 02                                                               5.0000E 00   3.6907E 01   2.5164E 01
6.6000E 00      4.2097E 02                                                               5.0000E 00   3.7907E 01   2.5846E 01
6.8000E 00      4.2865E 02                                                               5.0000E 00   3.8907E 01   2.6527E 01
7.0000E 00      4.3653E 02                                                               4.0000E 00   3.9897E 01   2.7202E 01
7.2000E 00      4.4453E 02                                                               4.0000E 00   4.0697E 01   2.7749E 01
7.4000E 00      4.5274E 02                                                               4.0000E 00   4.1495E 01   2.8293E 01
7.6000E 00      4.6116E 02                                                               4.0000E 00   4.2295E 01   2.8838E 01
7.8000E 00      4.6970E 02                                                               4.0000E 00   4.3096E 01   2.9384E 01
8.0000E 00      4.7839E 02                                                               4.0000E 00   4.3896E 01   2.9929E 01
8.2000E 00      4.8724E 02                                                               4.0000E 00   4.4695E 01   3.0475E 01
8.4000E 00      4.9625E 02                                                               4.0000E 00   4.5495E 01   3.1020E 01
8.6000E 00      5.0543E 02                                                               4.0000E 00   4.6296E 01   3.1565E 01
8.8000E 00      5.1475E 02                                                               3.0000E 00   4.6956E 01   3.2015E 01
9.0000E 00      5.2420E 02                                                               3.0000E 00   4.7556E 01   3.2424E 01
9.2000E 00      5.3375E 02                                                               3.0000E 00   4.8155E 01   3.2833E 01
9.4000E 00      5.4345E 02                                                               3.0000E 00   4.8755E 01   3.3242E 01
9.6000E 00      5.5325E 02                                                               3.0000E 00   4.9355E 01   3.3652E 01
9.8000E 00      5.6315E 02                                                               3.0000E 00   4.9955E 01   3.4061E 01
1.0000E 01      5.7323E 02                                                               3.0000E 00   5.0555E 01   3.4470E 01
1.0200E 01      5.8339E 02                                                               3.0000E 00   5.1155E 01   3.4879E 01
1.0400E 01      5.9364E 02                                                               3.0000E 00   5.1755E 01   3.5288E 01
1.0600E 01      6.0400E 02                                                               3.0000E 00   5.2355E 01   3.5697E 01
1.0800E 01      6.1461E 02                                                               3.0000E 00   5.2955E 01   3.6106E 01
1.1000E 01      6.2525E 02                                                               3.0000E 00   5.3555E 01   3.6515E 01
1.1200E 01      6.3602E 02                                                               3.0000E 00   5.4155E 01   3.6924E 01
1.1400E 01      6.4691E 02                                                               3.0000E 00   5.4755E 01   3.7333E 01
1.1600E 01      6.5791E 02                                                               3.0000E 00   5.5355E 01   3.7742E 01
1.1800E 01      6.6904E 02                                                               3.0000E 00   5.5955E 01   3.8151E 01
1.2000E 01      6.8028E 02                                                               3.0000E 00   5.6555E 01   3.8560E 01
1.2200E 01      6.9165E 02                                                               3.0000E 00   5.7155E 01   3.8969E 01
1.2400E 01      7.0313E 02                                                               3.0000E 00   5.7755E 01   3.9379E 01
1.2600E 01      7.1474E 02                                                               3.0000E 00   5.8355E 01   3.9788E 01
1.2800E 01      7.2645E 02                                                               3.0000E 00   5.8955E 01   4.0197E 01
1.3000E 01      7.3831E 02                                                               3.0000E 00   5.9555E 01   4.0606E 01
1.3200E 01      7.5029E 02                                                               3.0000E 00   6.0155E 01   4.1015E 01
1.3400E 01      7.6236E 02                                                               3.0000E 00   6.0755E 01   4.1424E 01
1.3600E 01      7.7457E 02                                                               3.0000E 00   6.1355E 01   4.1833E 01
1.3800E 01      7.8689E 02                                                               3.0000E 00   6.1955E 01   4.2242E 01
1.4000E 01      7.9931E 02                                                               3.0000E 00   6.2555E 01   4.2651E 01
1.4200E 01      8.1190E 02                                                               3.0000E 00   6.3155E 01   4.3060E 01
1.4400E 01      8.2459E 02                                                               3.0000E 00   6.3755E 01   4.3469E 01
1.4600E 01      8.3739E 02                                                               3.0000E 00   6.4355E 01   4.3879E 01
1.4800E 01      8.5032E 02                                                               3.0000E 00   6.4955E 01   4.4287E 01
1.5000E 01      8.6337E 02                                                               3.0000E 00   6.5555E 01   4.4697E 01
1.5200E 01      8.7653E 02                                                               0.0          6.6005E 01   4.5003E 01
```

Figure 20. Computer Output from Stopped-Gap Band Trajectory Analysis Program

the ramp signal in the Woburn system, and its use was implemented in Tampa to tailor the green band system performance to expected vehicle characteristics there.

Tests were conducted on the ramp in the stopped-gap made with a variety of vehicle types, ranging from light economy sedans to medium trucks, and the variable acceleration profile used was easily tracked by most of the drivers.

Green Band Generation (Tampa Variable Ramp Speed Case)

Data acquisition and highway vehicle processing for green band generation in the Tampa system are done in the same manner used in the Woburn system. Similarly, freeway gaps are measured and checked for adequacy by the same computer logic. What is unique to the Tampa system, however, is the method used to position bands on the display to accomplish the required objective of having bands which move at a fixed speed in the initial section of the ramp and then accelerate to the final merging velocity in the latter phase of their trajectories.

The maximum safe vehicle speed into the curved section of radius 230 feet on the Tampa ramp is 30 miles/hour. The design concept of the green band system is to project ramp vehicles into accepted gaps at a programmed merge velocity, VMRG, equal to the current three- minute average freeway speed, or 45 miles/hour, whichever is less. Thus, some means of accomplishing the dual goals of holding ramp vehicle speeds constant at 30 miles/hour through the initial section of the ramp, and then directing the acceleration of the ramp vehicles to the desired merge speeds was required. The use of several variable message speed signs positioned alongside the ramp showing the desired vehicle speed at those points was considered in conjunction with the green bands, but this approach was rejected as providing too much additional information to the drivers to assimilate in conjunction with the green band following task in the time required to drive the ramp.

Therefore, techniques had to be developed to make use of the only available control element, the moving green bands themselves to guide the drivers along safe merging trajectories. This was accomplished through changes made in the control program coding of the Green Band Status routine (GBS), which provides the band edge placements and associated band velocities. The nature of these changes will be discussed below, and details of the computer code used to implement these revisions may be found in the Tampa Green Band System Final Report, in preparation now for publication in the Summer of 1975 by the Transportation Research Center, University of Florida, Gainesville, Florida.

Consider the basic geometry and dimensions of the Ashley Street ramp and green band display element as being associated with points on a straight line, as indicated in Figure 21.

Now, consider the operations associated with computing the placement of a leading or trailing edge for a band on the display element, and with the computation of the current velocity of the leading edge of the band at this position, given that the final band speed is to be VMRG.

The algorithm developed for the Tampa Green Band System to accomplish the required placement decision for the band edges is a supporting subroutine to GBS in the on-line control program, and its structure is as follows (Steps 1 through 6 are always done in sequence):

1. Compute TMP, the time remaining to expected merge point arrival for this band edge from:

   TMP = (ETA + HDWY + LEN) - TIME,

   where ETA = estimated time of arrival at the merge point for the freeway vehicle associated with this edge of the band (seconds),

   HDWY = a leading or trailing headway allowance representing a merging

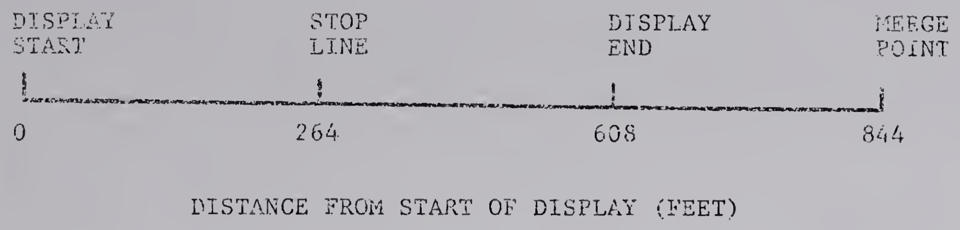


Figure 21. Linear Tampa Ramp Geometry

safety margin (0.4 seconds for a leading edge, 1.2 seconds for a trailing edge),

LEN = freeway vehicle length in seconds for a leading band edge (set to 0.0 seconds for a trailing edge),

and TIME = current time in seconds (maintained as an integer count of the elapsed number of previous .002-second clock cycles in the on-line system).

2. Compute DACC, the distance required for a band moving at 30 miles/hour during the first 264 feet of the ramp to accelerate to VMRG during the remainder of its time to merge point,

$$DACC = (VMRG^2 - 44^2)/2\alpha,$$

where VMRG = current terminal band speed, in feet/second, and 44 is 30 miles/hour in feet/second,

and α is an assumed acceleration rate of 3 feet/second^2 for the band.

3. Compute T_{const}, the time at which the band would travel at VMRG after completing its acceleration maneuver:

$$T_{const} = (580. - DACC)/VMRG,$$

where 580 feet is the distance from the stop line to the merge point.

4. Compute TAE, the time at which the current band is programmed to complete its acceleration maneuver (may be positive or negative),

   $TAE = TMP - T_{const}.$

5. Compute TSL, the time at which the band edge is programmed to be at the stop line point on the green band display (may be positive or negative),

   $TSL = TAE - ((VMRG - 44)/\alpha).$

6. Compute TBD, the time the current band edge is programmed to be at the beginning of the green band display (may be positive or negative),

   $TBD = TSL - 6,$

   where 6 is the time in seconds for a band to cross the initial section of 264 feet of the display at a velocity of 44 feet/second. Go to Step 7.

7. If TMP, the time to merge point for the band is negative, this band edge was at the merge point at a time in the past, and the following conditions are loaded into the green band table for this edge:

   $EDGE_i = + 844,$

   $VBAND_i = VMRG,$

and the routine returns to the calling point in GBS. Otherwise, go to Step 8.

8. If TAE, the time at which the band was programmed to stop accelerating, is negative, this band edge is now moving at VMRG and the green band table is loaded with:

   $EDGE_i = 844 - (VMRG*TMP)$

   $VBAND_i = VMRG$

   and the routine returns to the calling point in GBS. Otherwise, go to Step 9.

9. If TSL, the time at which the band was programmed to be at the stop line, is negative, the band is still accelerating, and the green band table for the current edge is loaded with:

   $EDGE_i = 44. - (UFTSL*\alpha)$

   $VBAND_i = 264. + VBAND_i^2 - 44^2)/2\alpha$

   and the routine returns to the calling point in GBS. Otherwise, go to Step 10.

10. None of the conditions identified in Steps 8, 9, or 10 has been met, and the current band edge must be either upstream of the beginning of the display, or travelling at a constant velocity of 30 miles/hour at some point within

the first 264 feet of the display. In either case, the green band table is loaded with;

$$EDGE_i = - TBD*44,$$

$$VBAND_i = 44. ,$$

and the routine returns to the calling point in GBS.

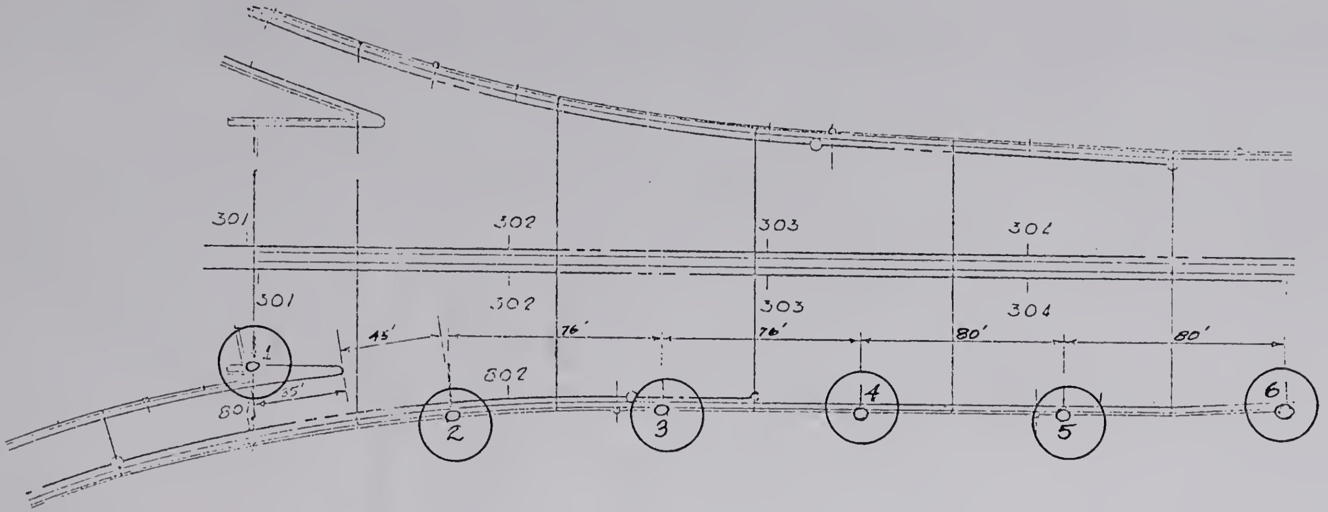
As in the Woburn system, band movement and positioning on the field display in Tampa is the joint result of the two processes of band creation by the GBS routine, and band movement by the GBUD routine, which take place in sequence at rates of 100 times per second for the Tampa system. Observed band sizes on the display do change dynamically to reflect changing gap sizes on the freeway, but it is important to note that these changes represent new bands, rather than the evolution of bands previously stored on the display.

The algorithm for band placement in Tampa represents a significant departure from that used in the Woburn system, and is representative of the types of "site-responsive" features that will have to be tailored into moving merge control systems for other ramps with unique geometric features.

Location of the Merge Point for the Tampa System

As discussed earlier in this chapter, the on-line green band control program searches for gaps in the outside freeway lane upstream of the entrance ramp, and computes the expected time of arrival of these gaps at a location adjacent to the ramp acceleration lane. This location is referred to as the merge point and represents the expected location at which the ramp vehicles will enter the freeway. Given the existence of an acceptable freeway gap, a green band is launched on the ramp display and propagated along the ramp such that its arrival time at the merge point corresponds to the expected arrival time of the freeway gap at the same location. Since all control updates of projected freeway gaps and of the green band display are made with reference to the merge point, the operation of the green band control system is highly dependent upon the merge point location parameter, and field studies were conducted to establish this location for use in the control software for the Tampa system.

For the purposes of this study, it was assumed that a ramp vehicle had merged when its left front wheel had crossed the dividing line between the ramp acceleration lane and the outside freeway lane, or equivalently, its right wheels were less than six feet from the dividing line. To measure the location of the merging point, then, six 15-minute traffic counters were placed in the acceleration portion of the ramp as shown in Figure 22. These units collected data from 3:30 A.M. on December 13, 1972, until 3:30 A.M. on the following day.



COUNTER NO.	ROAD-TUBE LENGTH	PURPOSE
1	12 feet	Outside Lane Volume on Freeway
2	12 feet	Ramp Volume
3-6	6 feet	Merge Distribution Counts

Figure 22. Placement of Traffic Counters for Merge Point Location Study

The 7-11 A.M. data and 3-7 P.M. data were plotted for different traffic conditions and times of day as shown in Figures 23 and 24. Figure 23 is a plot of the A.M. data, and gives the percentage of vehicles entering the freeway between the various count locations. Figure 24 is a plot of the percentage of vehicles passing a count location by hour for the 3 P.M. - 7 P.M. data. Analysis of the data indicated that the distribution of merge locations of observed vehicles was approximately uniform along the acceleration portion of the ramp, and no one location could be fixed as the merge point. The data did indicate that at a point approximately half-way down the ramp, the probability of a merge having taken place was 0.5, and therefore, a point half-way down the ramp was the median merge point for ramp vehicles. Since the ramp vehicles did not follow a merging distribution which indicated the existence of a fixed merge point, the median value was used as an estimator of this location. Considerations to extend this estimated location as far downstream on the ramp as possible were made, as the number of freeway sensors which could be used was constrained upstream by an exit ramp, and the location of the merge point further downstream would enhance the utilization of freeway sensor information, by allowing earlier band positioning updates which could contribute to the improved operational effectiveness of the merge control system.

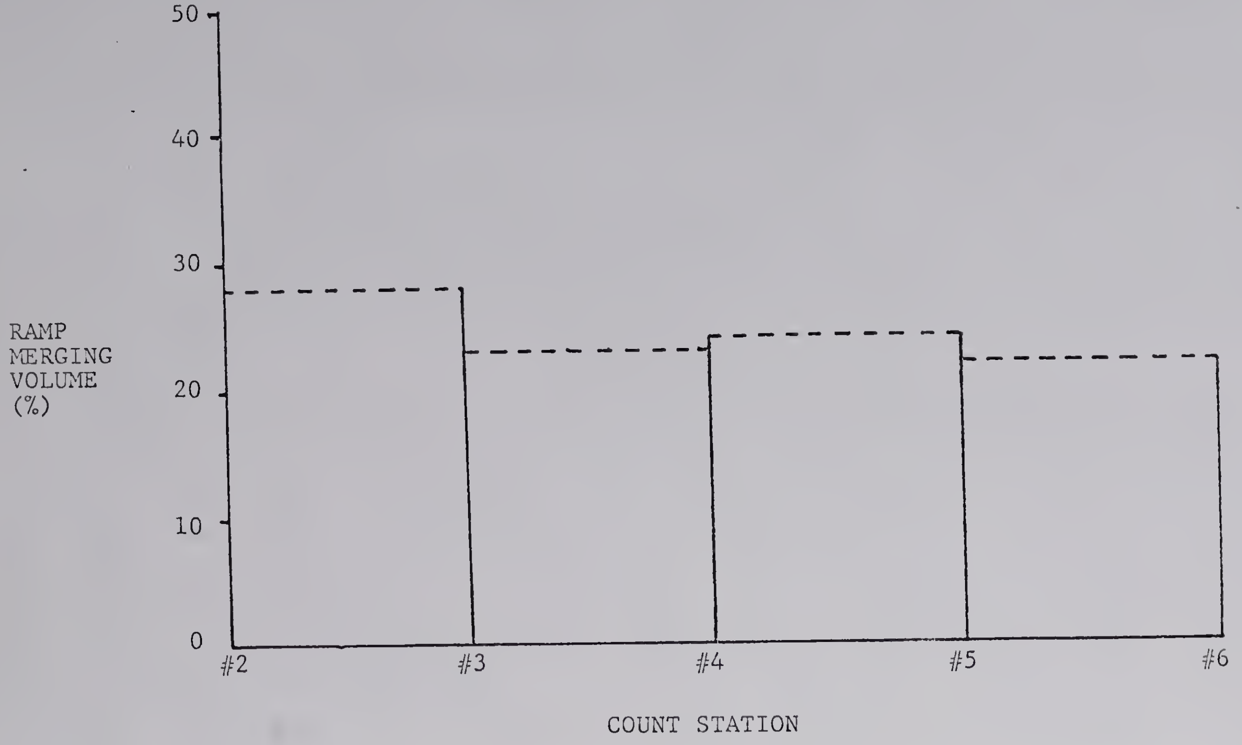


Figure 23. Distribution of Ramp Vehicles Entering Freeway by Count Station, 7 A.M. - 11 A.M., December 13, 1972

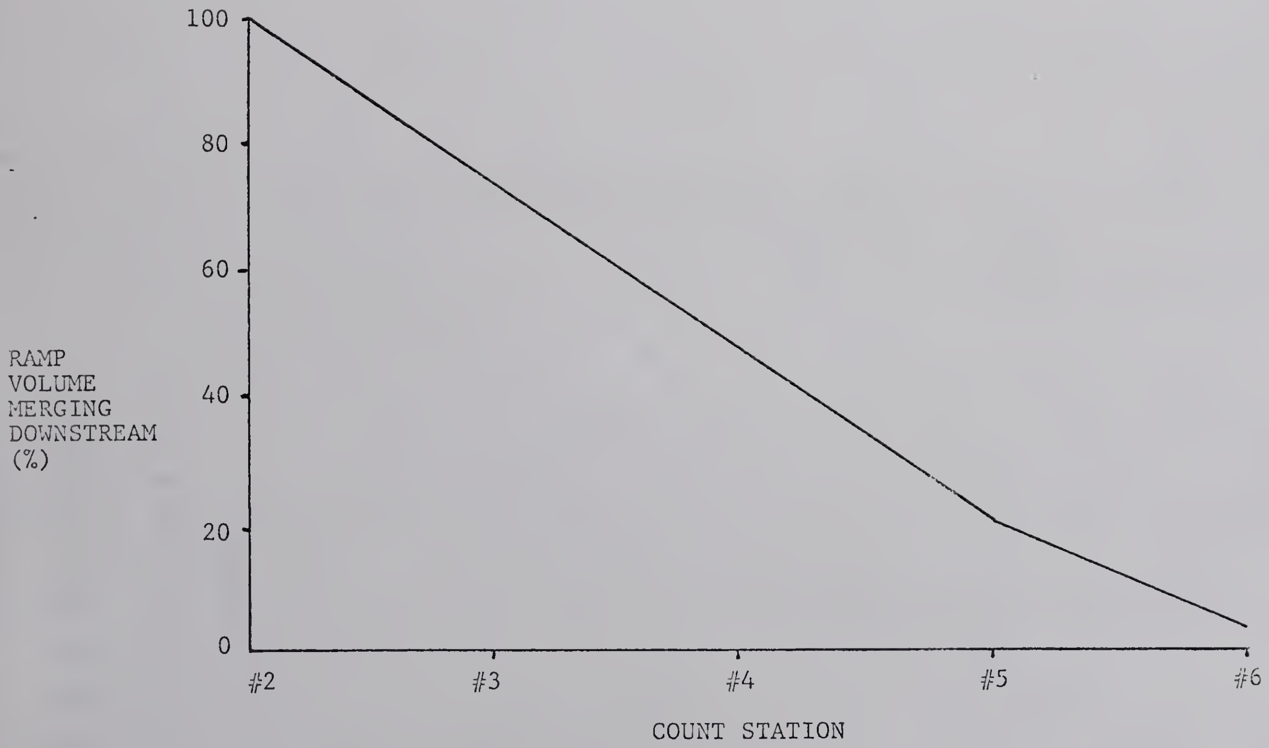


Figure 24. Per Cent of Ramp Vehicles Passing Count Stations, 3 P.M. - 7 P.M., December 13, 1972.

Under such considerations, then, the maximum usable downstream location of the merge point is a function of the safe stopping distance of a ramp vehicle unable to complete a directed merge. The assumption was made that the perception-reaction times for the driver involved in a stop would take place prior to the arrival of his vehicle at the merge point, then, if an acceptable gap was not available at a maximum downstream merge point location, the safe stopping distance, S_d, could be found from the expression:

$$S_d = \frac{V}{30\ (f \pm g)}$$

where V = vehicle velocity in miles/hour,

f = coefficient of friction of the road surface,

and g = the percent grade divided by 100.

The "worst-case" condition for stopping distance on the ramp was found by using the maximum ramp speed of 45 miles/hour as the 85th percentile speed in the expression, and by using a coefficient of friction of 0.25 (for a wet concrete pavement). Using these values,

$$S_d = \frac{(53)^2}{30\ (.25 \pm 0)} = 210 \text{ feet.}$$

The downstream end of the ramp is considered to be the point on the taper at which the ramp lane is eight feet wide. This point is 414 feet from the nose of the ramp. Therefore, the merge point location, based on a safe stopping distance, was 204 feet downstream of the ramp nose. This location is approximately the same value as the merge point location of 207 feet downstream determined by using the merge distribution results. Figure 25 shows the location of the merge point for the Ashley Street eastbound entrance ramp selected for use in the merge control system.

Freeway Detector Placement for the Tampa Green Band System

The critical function of the green band control software is to project acceptable gaps to the merge area and to fit ramp vehicles into these gaps with moving green bands. For both freeway gap and ramp vehicle to converge at the same point in time, their respective travel times through their upstream approaches must, in the worst case be equal. This requires an adequate length of system surveillance and control area for these movements to occur, considering the program control strategy, which can be expressed in time as:

$$T_r \leq T_f + G_c,$$

where T_r = Travel time of ramp vehicle through the green band display to the merge area (seconds),

T_f = Travel time of freeway vehicle leading the gap from first sensor to merge area (seconds),

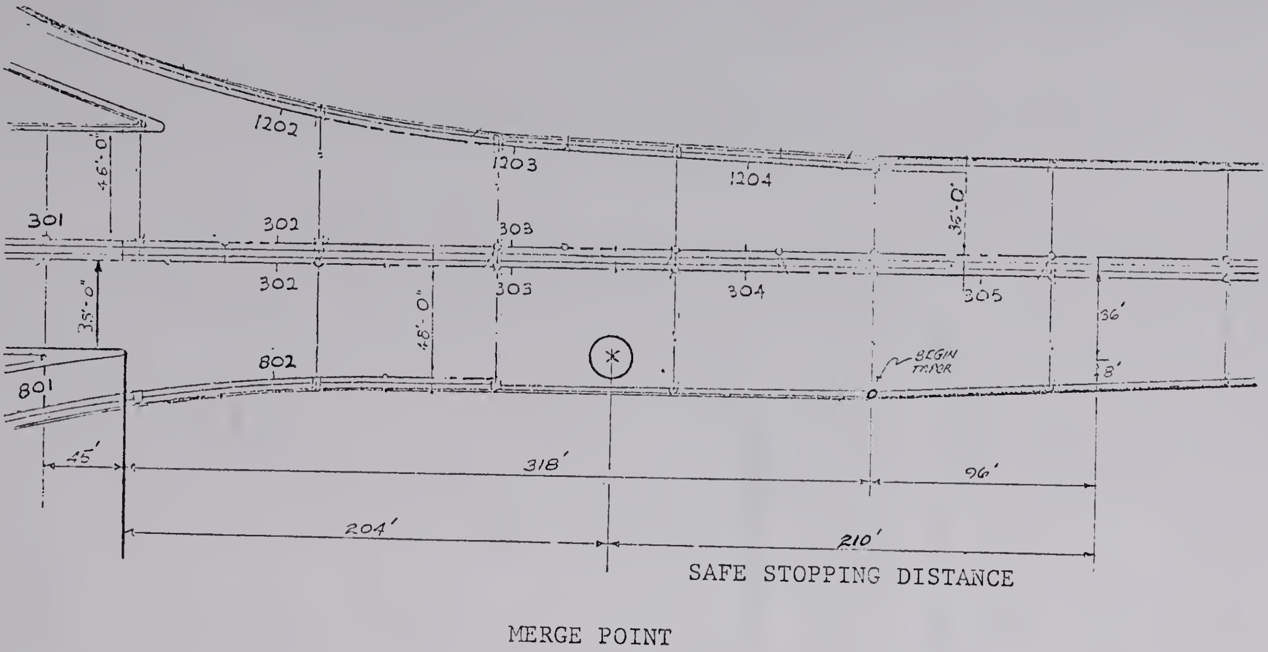


Figure 25. Location of Merge Point for the Tampa System

G_c = Acceptable gap size on the freeway (seconds).

Preliminary calculations based on projected ramp speeds in Tampa showed T_r to be about 14.7 seconds. This required the first system input sensor on the freeway to be at least 1,600 feet upstream of the merge are (assuming 60 miles/hour speeds on the freeway, and a 3.5 second critical gap as representative). The merging area study resulted in the downstream characteristics of the freeway surveillance area, but given the geometrics of the Ashley site, these calculations showed that the first freeway sensor station would have to be located upstream of the exit ramp to the west of the Ashley ramp.

To develop criteria for the final sensor placement decisions in the system, then, the freeway and ramp vehicle travel time characteristics had to be accurately established in terms which would permit a predictable level of performance of the control system at high freeway speeds, and a study was conducted to provide these data [92]. Manual detections of vehicle activity were recorded on a twenty-pen strip chart recorder. Data were recorded simultaneously for right lane freeway and ramp traffic for reduction and analysis by digital computer. The study plan was as shown in Figure 26. An observer at point A recorded by manual inputs the entrance of either a freeway vehicle (at point B) or a

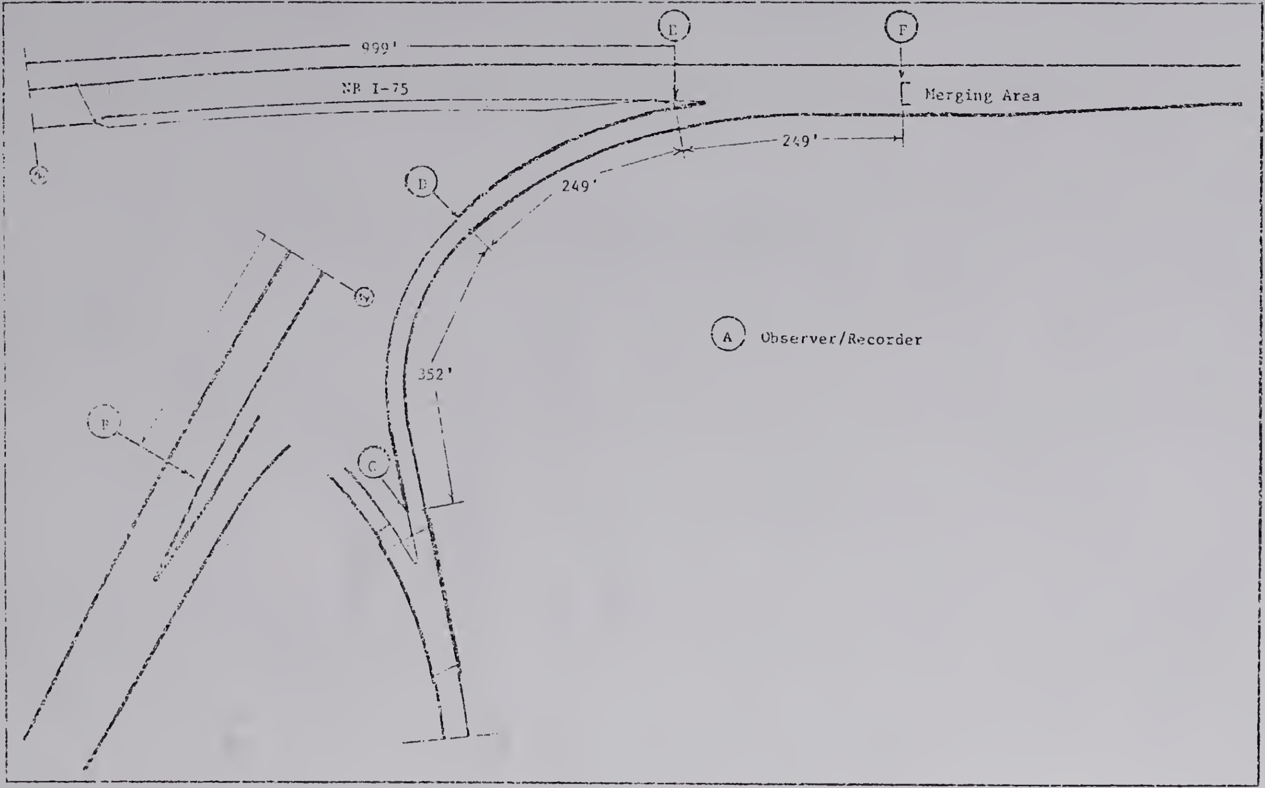


Figure 26. Surveillance Area for Travel Time Study

ramp vehicle (at point C) into their respective study sections. (Due to the distance between A and B, a second observer was at B, advising observer at A when the freeway vehicles passed the station by radio communication). Observer A then recorded when each freeway vehicle passed point I or the progression of a ramp vehicle through points D, E, and F. Point F was a floating point at which, in the observer's judgment, ramp vehicle merging had occurred (e.g., the left front wheel had crossed the lane divider). The data were analyzed by an off-line computer program which computed the mean travel times and mean average speeds of vehicles between study points. Using the separate volume counts, these stations were plotted for the critical conditions, considering the timing relationship given earlier. Findings were correlated with results of the Merging Area Study for evaluation of the ramp travel time between points E and F.

Data were taken for the period of 3:00 to 5:30 P.M. on December 13, 1972. Freeway data included random vehicles since the objective was to determine expected travel times under normal conditions. Ramp observations were limited to vehicles which moved unrestricted through the ramp to a merge since the aim of the study was to identify the standardized driver and vehicle performance capabilities which would be assisted by green band control. The results of this study are shown in Table 3.

Table 3
Results of Travel-Time Study

Freeway Traffic

Travel Time (1)

Start Time	Sample Size	Mean (Seconds)	Std. Deviation (Seconds)	Mean Vehicle Speed (Miles/Hour)
3:00	10	12.90	2.16	52.78
3:15	23	12.41	1.47	54.88
3:30	26	12.54	1.45	54.33
3:45	18	13.25	1.43	51.42
4:00	10	13.77	1.62	49.46 (2)
4:15	10	12.59	1.87	54.09
4:30	12	13.01	1.83	52.36
4:45	11	13.37	1.04	50.96
5:00	14	14.46	1.95	47.09
5:15	9	13.68	2.42	49.78

Ramp Traffic

Time Period: 3:00 - 5:30 P.M., Sample size = 70 vehicles

Travel Time

Section	Mean (Seconds)	Std. Deviation (Seconds)	Mean Vehicle Speed (Miles/Hour)
C-D	6.98	0.76	34.39
D-E	5.39	0.75	31.50
C-D	12.37	1.41	33.13
E-F	5.01	1.36	(3)

Notes:
(1) Section B-E.
(2) Congestion existed during this period caused by a downstream bottleneck.
(3) Not determined since distance is variable.

Selection of the critical results requires some explanation. Keeping in mind that velocity values for the freeway should be as high as possible for conservative system design, then the results of the period 3:15 - 3:30 were selected. It was further assumed that this period represented the 85th percentile speed, so the maximum design speed was 64.47 miles/hour or 64.5 miles/hour (95.3 feet/second), and the equivalent travel time was about 10.7 seconds through section B-E). As only unconstrained ramp vehicles were considered, the aggregated results gave the information required. These values are plotted in Figure 27. It was assumed that freeway speeds are uniformly distributed beyond points B and E. Since the approach to point B is a positive grade and point E is near the merging area (where speeds are not likely to increase significantly), this appeared to be a safe assumption. It was not possible in this study to calculate ramp vehicle speeds for section E-F; however, recall that the basic objective of the control system is to merge the ramp vehicles at a speed representing some fraction of the speed of the freeway traffic. Thus, if freeway speeds were at a maximum, a conservative speed for ramp vehicles here is 54.2 miles/hour (average of GB speed at nose = 45 miles/hour and freeway speed). Then, extending data observed in the study, and assuming an available acceptable gap (which must be detected before the green band will

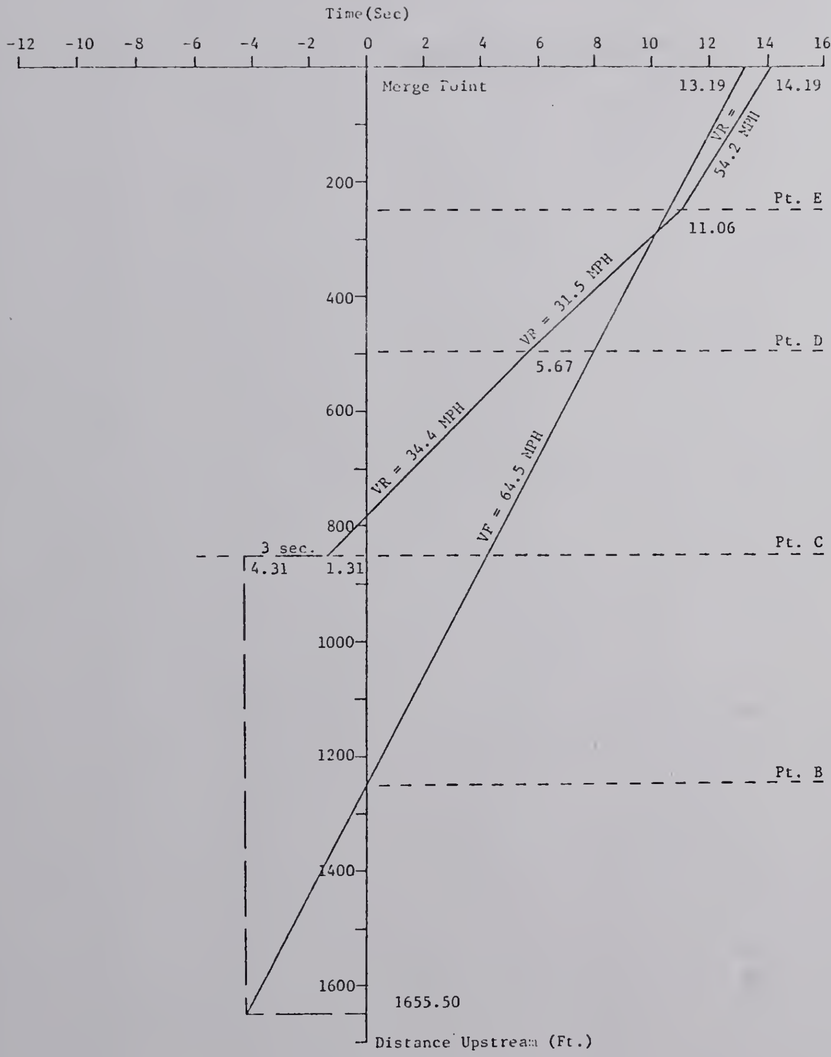


Figure 27. Space-Time Diagram for Maximum Expected Speeds

be generated) and drawing the intersect where:

$$T_r = T_F + G_c + H_1$$

where T_r, T_F and G_c are as previously defined, and

H_1 = leading headway between ramp and freeway vehicles, assumed to be one second,

it is determined that the first freeway station must be 1,655.5 feet upstream of the merge point, or 1,406.5 feet upstream of the concrete nose of the ramp.

It had to be determined if this location would satisfy the lower condition, e.g., when freeway speeds are 35 miles/hour. Again, this condition applied at the end of the ramp; and for the purpose of this study, a ramp speed of 2/3 V_f was assumed. These values required an upstream distance of 1,253.6 feet--well within the earlier findings (see Figure 28). The conclusion was reached that the first detector station on the freeway would be located at a point 1,406.5 feet upstream of the entrance ramp nose. This location is about 326 feet upstream of the nose of the Ashley exit ramp, a fact which introduces the possibility of false signals from this station, since for example, a vehicle may be detected as part of the freeway stream but then exit the freeway, possibly leaving an acceptable gap, or a vehicle in the exit lane may merge back into the freeway outside lane after the station (thus pos-

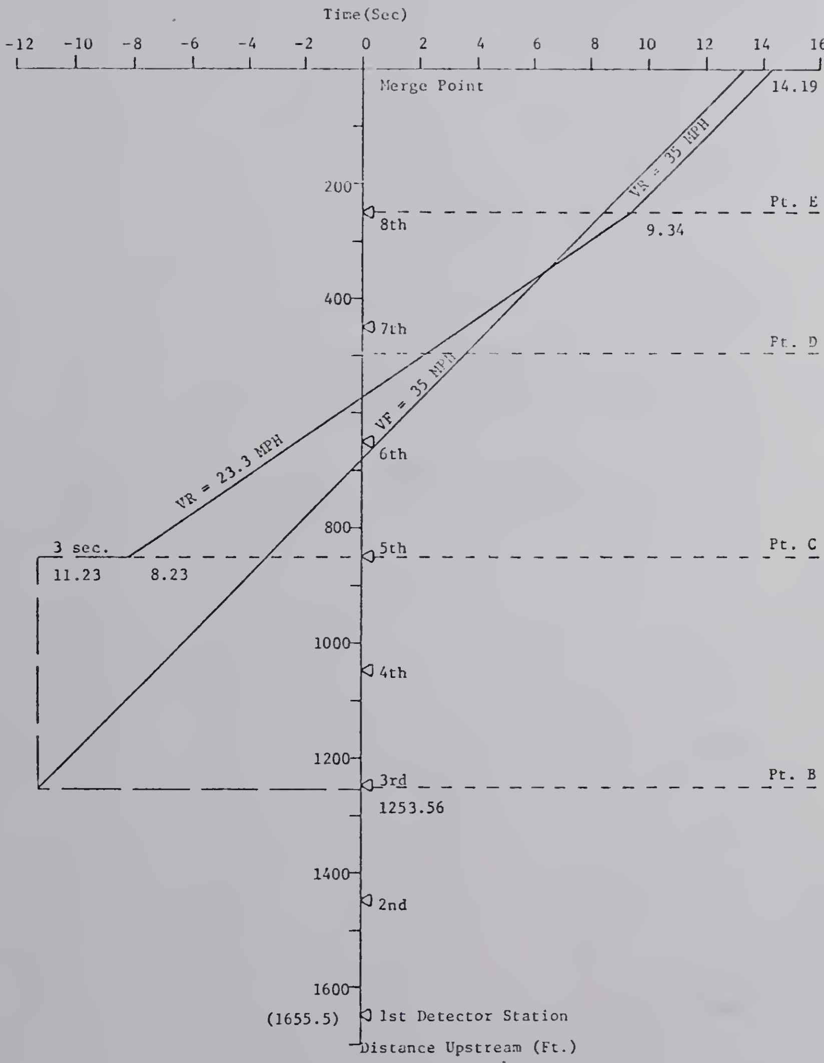


Figure 28. Space-Time Diagram for Minimum Expected Speeds

sibly filling a gap already processed as being acceptable). The latter case is easily handled by the control program which will delete the green band, leading to an actuation of the yield sign on the ramp if the resulting two gaps are both unacceptable when downstream sensors reveal the gap is filled. Any ramp vehicle driver who was following the green band will naturally continue to merge eventually, but he will also be properly advised that no acceptable gap is available.

The former situation will tend to "waste" some acceptable gaps, but not as frequently as might be expected. In the higher freeway speed ranges such losses will undoubtedly result because of the travel time constraints as shown in Figure 27; however, the false move is less likely to occur at these speeds. In the lower freeway speed ranges it will still be possible to "flag" an acceptable gap when downstream detectors sense that such is the case. An example is shown in Figure 29 for freeway speeds of 45 miles/hour, with ramp speeds adjusted accordingly. The freeway gap could be detected at a point 1,197.2 feet upstream or approximately at the third freeway detector station in the system (if the stations are 200 feet apart).

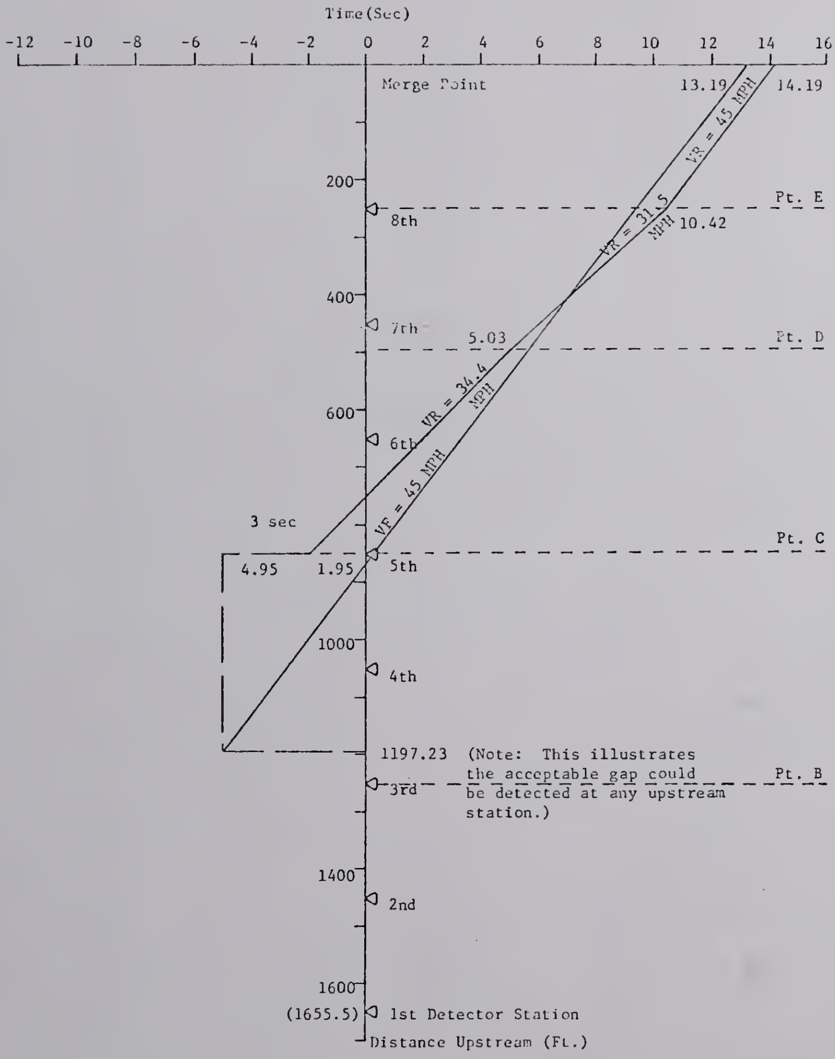


Figure 29. Space-Time Diagram for Mid-Range Speeds

Location of Ramp Detectors and Stop Line

The locations of the detectors on the ramp were fixed by considering the location of the YIELD sign control detector, R3, and then assuming a ramp loop detector edge spacing of 64 feet. The factors used in determining the placement of detector R3 were: (1) the detector should be placed far enough up the ramp so that drivers would have a minimum of one second of viewing time if the green band is aborted, and the yield sign has to be illuminated, and (2) the control system implications of the location of the last usable update detector on the freeway for green band programming had to be evaluated for this detector location.

With these criteria in mind, the location of detector R3 was determined in the following manner. Assuming that the YIELD sign is located at point E, on Figure 30, the minimum distance upstream from the sign that will afford a ramp driver, traveling at 45 miles/hour, the minimum viewing time of one second is 45 miles/hour x 1.467(feet/second)/(miles/hour) x 1 second = 66.0 feet. This represents the minimum distance to point E that detector R3 could possibly be located. Using this minimum distance and an assumed minimum acceptable gap length of three seconds, Figure 30 shows that the trailing edge would have to be detected approximately 595 feet upstream from the merge point. This

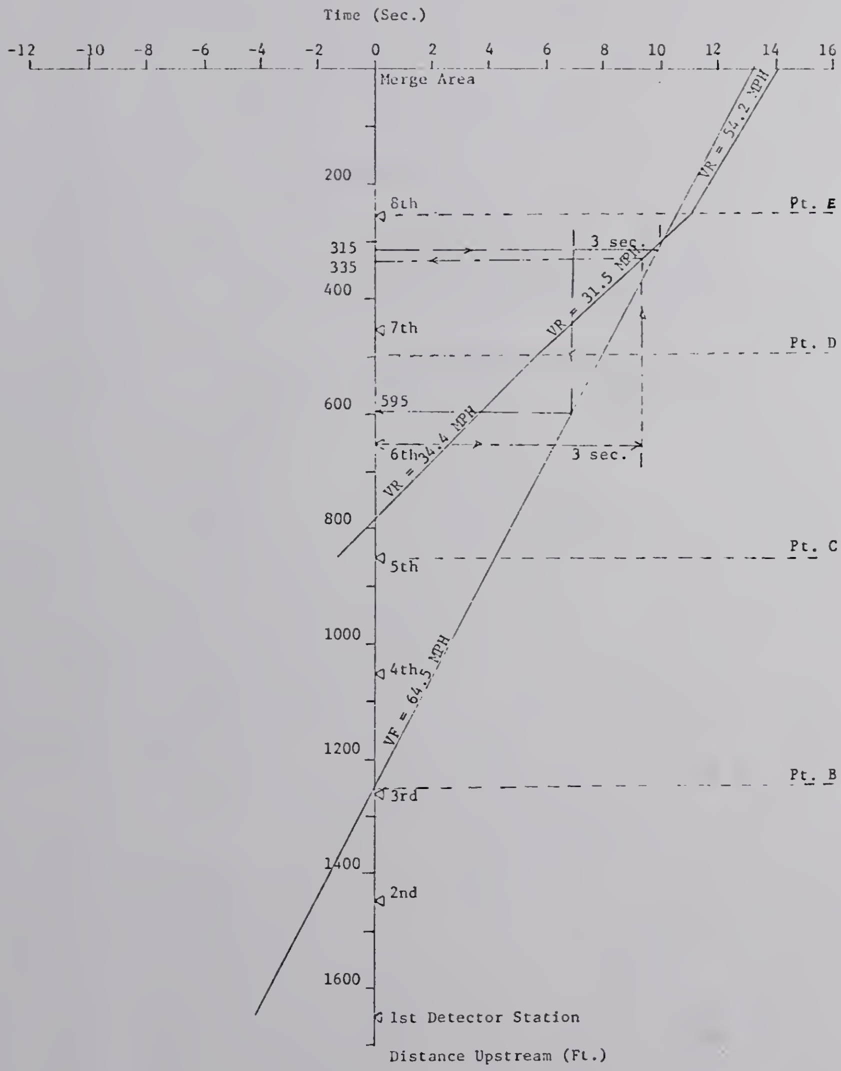


Figure 30. Space-Time Diagram for the Location of Tampa Ramp Detector R3

result indicated that freeway detector station 6 was the last usable update detector. Projecting back from this point, the location of detector R3 is found to be 86 feet upstream on the ramp from point E. With the location of detector R3 fixed, the locations of the other ramp detectors were found by proceeding back up the ramp with the assumed 64 feet detector spacing.

The stop line and associated traffic signal location was originally determined to give the ramp driver an adequate distance to accelerate from a full stop at the stop bar to the maximum speed required at point E of approximately 35 miles/hour in the stopped-gap operating mode.

The minimum distance required was then:

$$d = \frac{(V_f - V_o)^2}{2a}$$

where:

V_o = initial velocity in feet/second,

V_f = final velocity in feet/second,

and a = constant vehicle acceleration in feet/second^2.

Assuming a rate of acceleration of 4 feet/second^2,

$$d = \frac{(35 \times 1.47)^2}{2 \times 4} = 2647.1/8 = 330.8 \text{ feet.}$$

An actual stop line placement of 344 feet upstream of the YIELD sign was used in the final design to facilitate connections of the stop light and associated detector equipment to a previously installed equipment cabinet near the ramp.

Recall that the Woburn Green Band System used an acceleration rate of 4 feet/second^2 for stopped-gap band projection, and the analysis above was conducted in early 1973 using this value. With the availability of the Tignor paper [88] in the Summer of 1974, it was determined that a variable acceleration profile would be used for stopped-gap band control in the Tampa system for the reasons cited earlier.

This use of a different band acceleration assumption required the reconsideration of the adequacy of the placement of the ramp stop line under the new conditions, as the ramp markings and signal and detector placements had been completed at the location determined above. The simulation model for band trajectory analysis, and its output, shown in Figures 19 and 20, respectively, were used for this task. Assuming the new acceleration model was controlling the bands, a band launched at the stop line initialization point of 292 feet along the display will be moving at a velocity of 52.35 feet/second, or 35.69 miles/hour at the end of the display, which is 608 - 292 = 316 feet downstream. Thus, the new acceleration model could be used for stopped-gap operations with the stop line placement implemented for the earlier constant acceleration control strategy.

CHAPTER 4
ANALYSIS OF TAMPA SYSTEM PERFORMANCE

Objectives of the Evaluation

Historical traffic operational experience has shown that the areas with the greatest degree of congestion and the highest accident rates on urban freeways occur at the entrance ramps to these facilities (in spite of the fact that freeways are generally safer to use than are surface streets). The general causes of accidents at such locations relate to the following factors [86]:

1. Poor visibility due to bad geometric designs or environmental conditions.

2. The necessity for the ramp driver to monitor a number of moving vehicles on the freeway (mostly upstream relative to his position) and other ramp vehicles moving ahead of him, thus dividing his attention in two opposing directions.

3. The ramp driver has difficulty in accurately estimating the speeds of vehicles on the freeway.

4. The ramp driver must also monitor conditions in any queue of vehicles which may be stopped in the merge area waiting for gaps in the stream of freeway traffic.

5. The existence of short acceleration lanes at many existing freeway entrance ramps significantly increases the number of accidents on these ramps, as acceleration lanes of less than 200-foot length have been shown to have an accident rate approximately 60% higher than have those with a length of 700 feet or greater.

One obvious way to improve the merging process associated with conditions above then, is to improve the geometrics of the intersection of the on-ramp with the freeway facility, for example, to design the ramp to provide optimum visibility of freeway traffic in its initial section, and to provide an acceleration lane with a length of at least 700 feet to assist drivers in the merging maneuver. The provision of adequate geometry, however, may not be practical in the case of existing facilities, as very often the additional land space over that required by a more restricted design is simply not available, particularly in crowded urban areas. Also, reconstruction of existing facilities can prove to be extremely costly.

An alternative to reconstruction, then, is the provision of a ramp merging control system capability at an entrance ramp location. Properly designed ramp control systems tend to help alleviate all of the potential problem areas associated with many existing ramps outlined above. For example, the requirement for individual tracking of freeway vehicles by ramp drivers is theoretically eliminated with such systems, as the system hardware and software does this task in the preparation of its control decisions. In addition, control strategies can be designed which alleviate the problem of ramp vehicle congestion in the merging area, removing the need for ramp driver to monitor the other vehicles which have preceded him there.

The green band moving merge control system concept provides the ramp driver with information he finds difficult to ascertain for himself in three categories:

1. The availability of an acceptable gap,
2. The speed at which to travel to position himself in this gap, and
3. The alignment within the gap (e.g., should he be at the front end of the gap, in the middle of the gap, or at the rear of the gap).

As indicated earlier, the goal of any moving merge control system is to improve the merging operations of the freeway ramp by overcoming the various problems associated with its operation. The purpose of the research involving the Tampa Green Band System, then, is to determine if this mission has been accomplished successfully, and if the green band merge control system represents a feasible (or cost-effective) solution to the problem.

Specifically, the objectives of the final evaluation plan developed for the Tampa Green Band System were to determine the following conditions [74]:

1. The degree of improvement in freeway operations.
2. The degree of improvement in ramp operations and merging capacities.
3. The degree of ramp driver assistance provided by the system.
4. The reliability of system operations.
5. The cost/effectiveness of the system (as compared to the alternative of reconstruction to correct existing geometric design problems).

The evaluation uses both quantitative and qualitative data for the various analyses, the former consisting primarily of field detector data recorded on-line by the control computer associated with the system for subsequent off-line evaluation, and human factors driver performance data, and the latter primarily resulting from a public questionnaire survey.

A "before" vs. "after" performance study of ramp and freeway activity comprises the basic design of the overall evaluation plan. Table 4 summarizes all of the analyses to be conducted. Coding for the data sources indicated in the table is as follows:

A - field detector to computer tape (recorded on-line by the control system)

B - closed circuit television and video tape

C - available public record

D - instrumented vehicle

E - public questionnaire

Data sources in each category are further classified as primary (P) or secondary (S) for each study activity.

Table 4
Summary of Evaluation Plan

OBJECTIVE	ANALYSES	DATA SOURCE A	DATA SOURCE 3	DATA SOURCE C	DATA SOURCE D	DATA SOURCE E	ANTICIPATED RESULT
I. Improvement in Freeway Operation	1. Acceleration noise in freeway right lane.	P					1. Decrease in noise.
	2. Lane distribution on freeway.	P					2. Stabilizes toward outside lane.
	3. Lane change distribution in freeway right lane.	P					3. Fewer occurrences.
	4. Speed profile in freeway right lane.	P					4. Increase in profile.
	5. Freeway/ramp volume related to level of service.	P					5. Ratio decreases.
	6. Accident analyses - change in frequency.		S	P			6. Decline in rate.
	7. Conflict analysis						7. Decline in rate.
II. Improvement in Ramp Operations and Merging Capacity	1. Acceleration noise on the ramp.	P					1. Decrease in noise.
	2. Merging speed (ramp and freeway) related to volume.	P					2. Overall increase.
	3. Merging delay.	P					3. Decreased delay.
	4. Speed profile of ramp vehicles.	P					4. Overall increase.
	5. Acceptable gap distribution and critical gap.	P					5. Both diminish.
	6. Accident analyses - change in frequency.		S	P			6. Decline in rate.
	7. Conflict analysis						7. Decline in rate.
III. Amount of Driver Assistance	1. Speed profile of ramp vehicle.	P					1. Overall increase.
	2. Merge point distribution.	P					2. More modal.
	3. Acceptable gap distribution and critical gap.	P					3. Both diminish.
	4. Driver stress.				P	S	4. Tension decreased.
	5. Utilization of displays.	P	S				5. High degree.
	6. Effect of display utilization on driver success.	P					6. High degree.
	7. Public acceptance.					P	7. High degree.
IV. System Operation	1. System modal characteristics.	P	S				1. Stable operation.
	2. Utilization of displays.	P	S				2. High degree
V. Cost/Effectiveness	1. Analytical studies.						1. Economically Feasible.

In addition to the above data sources, cost data for the reconstruction alternative will be estimated and furnished by the Florida State Department of Transportation, and will be used in the final cost effectiveness evaluation of the ramp control system. Figure 31 shows an overall flow diagram of the evaluation plan, which consists of a number of parallel study activities. As the scope of this dissertation relating to the evaluation phase of the Tampa project includes only those areas involving the generation and analysis of computerized performance data, the other data collection tasks will be outlined only briefly for background; full details on these activities may be found in the Tampa Interim Project Reports [92-95].

Measurement Techniques: Human Factors Study

Discussions with research psychologists at the University of Florida had indicated the practical difficulty of using standard physiological measures of human stress conditions such as galvanic skin response (GSR) or heartbeat rate over the short periods of time the test drivers would be in the system (10-15 seconds, on the average), both from the standpoint of the required equipment complexity and possible degree of insufficient time availability in the test runs to establish significant statistical conclusions on before and after driver performance.

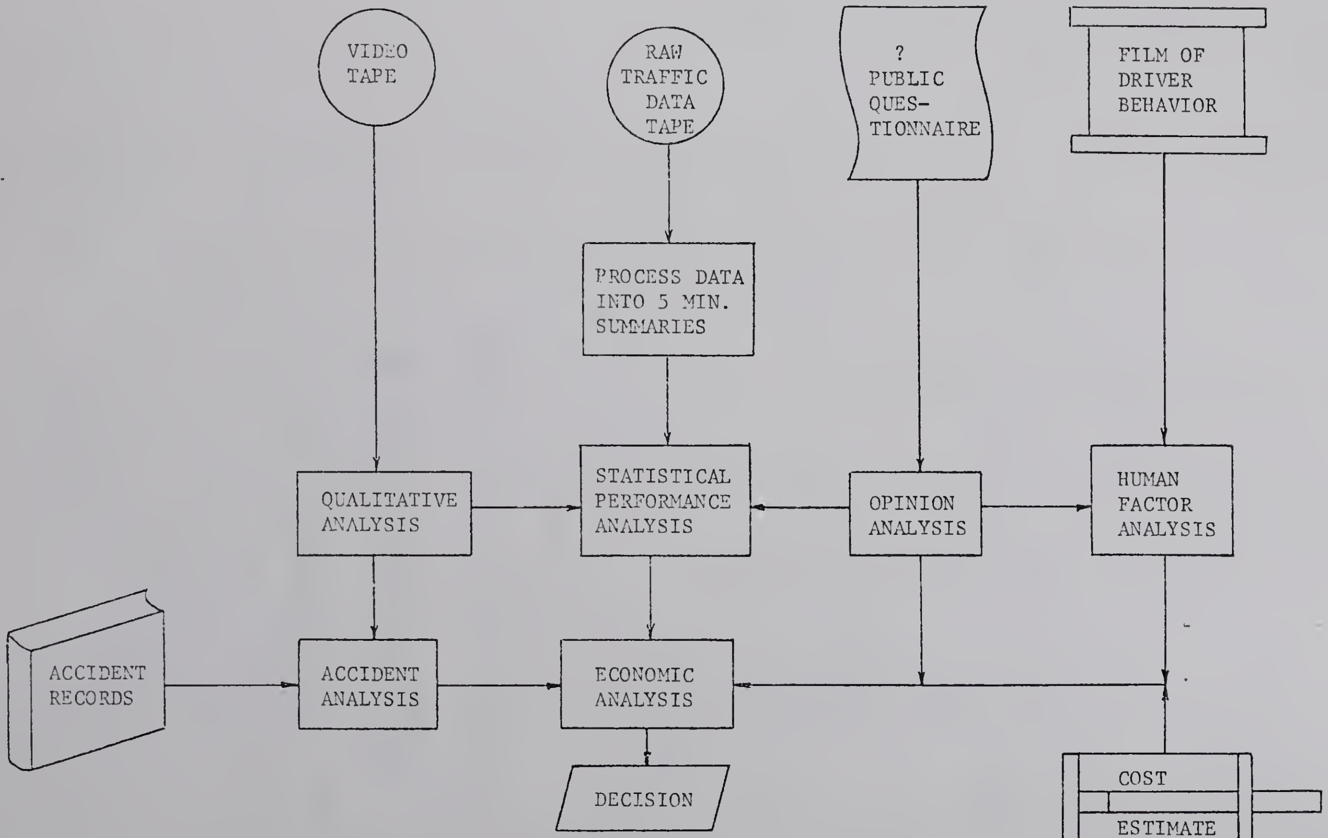


Figure 31. Evaluation Plan Flow Diagram

Therefore, an alternate approach of measuring driver reactions in the merging maneuver was developed, based on the observed external behavioral responses of the test subjects while they drove the ramp and entered the freeway [74, 76].

Studies of driver behavior were conducted for the Tampa Green Band System using test subjects driving an instrumented vehicle. These subjects were monitored by a data recording camera located in the back seat of the vehicle behind the driver position, which photographed driver's head movements in a plastic mirror suspended over the driver on specially constructed support framework. Located in the field of view of the camera was a light wired into the vehicle braking system giving an indication of driver brake applications. Twenty-two test subjects were asked to drive the ramp both before and after the control system went into operation. The resulting photographic data from these sutdies will be analyzed to produce measures of the following factors:

1. Average speed and travel time through the ramp system (also available from ramp sensors);
2. Frequency, magnitude, and duration of head movements of drivers while on the ramp;

3. Count of brake applications throughout the merging maneuver.

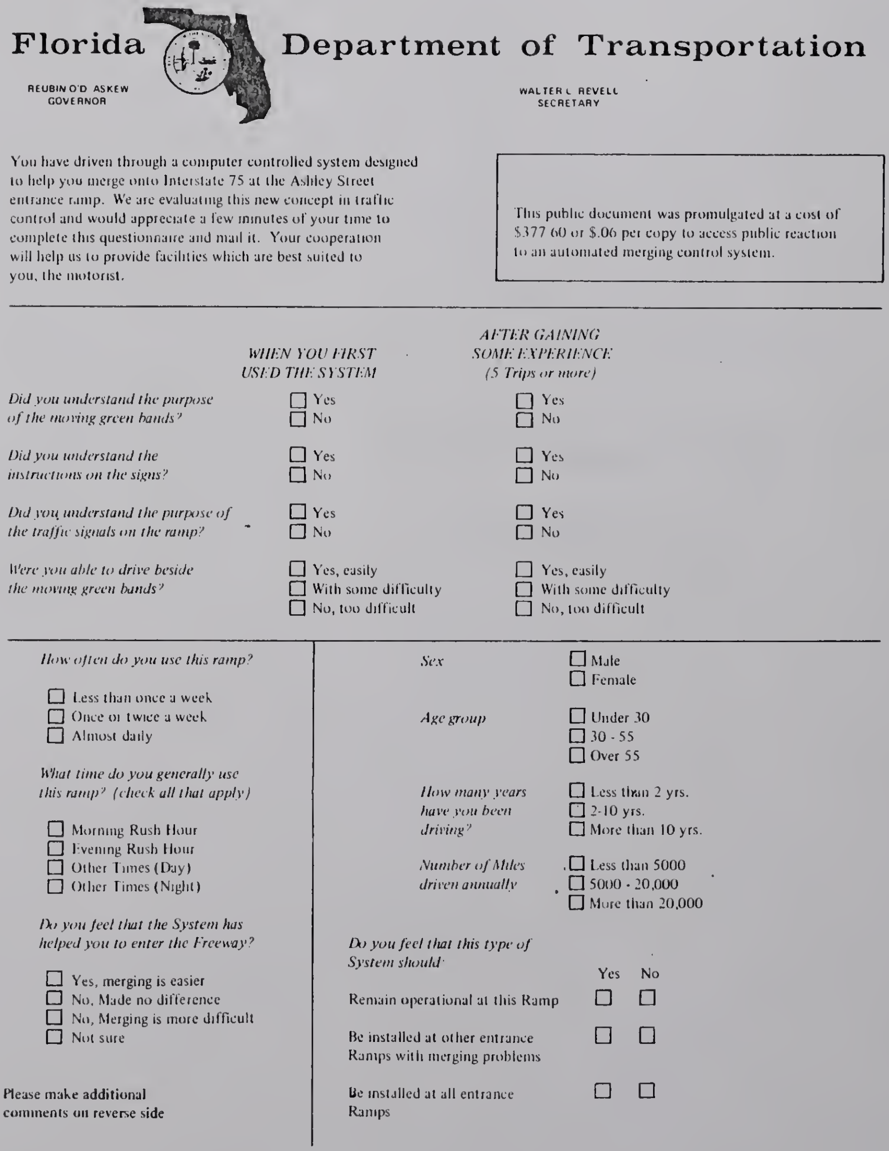
Statistical analyses will include paired tests of the performance of each test driver in the system for before and after conditions. The before studies were conducted in March of 1974 and the resulting photographic data have been reduced to computer cards for analysis by a computer program designed to produce the measures outlined above. The after studies were conducted in December of 1974 and this photographic data are currently under analysis.

Measurement Techniques: Public Opinion Study

Public operation of the green band system in Tampa began on July 31, 1974. Experimentation with the configuration of the control software and with system parameter values was conducted for a period of several months and the technical advisory committee for the project agreed on the final system design configuration in November of 1974. This final system was used by the public for approximately one month, and survey questionnaires were handed out to ramp drivers on December 15, 1974, from 7:00 A.M. to 4:00 P.M. Ramp drivers were asked to answer a series of questions and to return the form to a post office box in Tampa for subsequent evaluation by the project staff. Figure 32 shows the final design of this questionnaire.

At the time of this writing, some 600 questionnaires out of the 3,000 distributed earlier have been received, representing a return of over 20%. The replies from these forms will be keypunched for computer analysis and used to generate statistical classifications of the answers. An additional driver survey using this same questionnaire is planned to assess driver reactions during peak period system operation, e.g., the questionnaire distribution for this study will be in the 4:00 PM to 7:00 P.M. period only.

A limited manual analysis of the first set of completed questionnaires was done on the question: "Do you feel that this type of system should remain operational at this ramp?" 61% of those drivers responding answered in the affirmative, 33% answered no, and 6% gave no opinion. While definitive conclusions on public reaction must await the completion of the full analysis, the replies in this one category indicate a generally favorable public reaction to the green band system in Tampa.



Florida Department of Transportation

REUBIN O'D ASKEW
GOVERNOR

WALTER L REVELL
SECRETARY

You have driven through a computer controlled system designed to help you merge onto Interstate 75 at the Ashley Street entrance ramp. We are evaluating this new concept in traffic control and would appreciate a few minutes of your time to complete this questionnaire and mail it. Your cooperation will help us to provide facilities which are best suited to you, the motorist.

This public document was promulgated at a cost of $377.60 or $.06 per copy to access public reaction to an automated merging control system.

	WHEN YOU FIRST USED THE SYSTEM	*AFTER GAINING SOME EXPERIENCE (5 Trips or more)*
Did you understand the purpose of the moving green bands?	☐ Yes ☐ No	☐ Yes ☐ No
Did you understand the instructions on the signs?	☐ Yes ☐ No	☐ Yes ☐ No
Did you understand the purpose of the traffic signals on the ramp?	☐ Yes ☐ No	☐ Yes ☐ No
Were you able to drive beside the moving green bands?	☐ Yes, easily ☐ With some difficulty ☐ No, too difficult	☐ Yes, easily ☐ With some difficulty ☐ No, too difficult

How often do you use this ramp?

☐ Less than once a week
☐ Once or twice a week
☐ Almost daily

What time do you generally use this ramp? (check all that apply)

☐ Morning Rush Hour
☐ Evening Rush Hour
☐ Other Times (Day)
☐ Other Times (Night)

Do you feel that the System has helped you to enter the Freeway?

☐ Yes, merging is easier
☐ No, Made no difference
☐ No, Merging is more difficult
☐ Not sure

Please make additional comments on reverse side

Sex	☐ Male ☐ Female
Age group	☐ Under 30 ☐ 30 - 55 ☐ Over 55
How many years have you been driving?	☐ Less than 2 yrs. ☐ 2-10 yrs. ☐ More than 10 yrs.
Number of Miles driven annually	☐ Less than 5000 ☐ 5000 - 20,000 ☐ More than 20,000

Do you feel that this type of System should:

	Yes	No
Remain operational at this Ramp	☐	☐
Be installed at other entrance Ramps with merging problems	☐	☐
Be installed at all entrance Ramps	☐	☐

Figure 32. Public Opinion Questionnaire for Tampa Green Band System Evaluation

Measurement Techniques: Computer Analysis of Field Sensor Data

Recall that the Woburn Green Band System ramp control program checked field sensor status 500 times per second, and wrote all four sensor status words and the system time word onto magnetic tape if any one bit changed status from on to off or off to on. This approach required the recording of five data words or ten 8-bit bytes for one sensor bit changing levels in the worst case, and was potentially capable of producing a relatively high tape-writing overhead work load on the overall computer performance associated with the system. Recall also the use of 140-word buffers for writing the assembled sensor data onto the tape in the system, as was represented in Figure 8 of Chapter 2. The Woburn data logging program used two 140-word buffers for the data logging process, writing in one buffer in core memory while the other buffer was being written to the tape. When the current core buffer was full, the process was reversed to continue the data logging operations.

The instrumentation system installed in the field for the Tampa Green Band System was reviewed in Chapter 3 and depicted in Figure 14. The assignment of the various field sensor channels to the input hardware buffer words used in the Tampa Green Band System is shown in Figure 33. Four 16-bit words were available for input purposes in the

R9	●	F1B	F1A	F2B	F2A	F3B	F3A	F4B	F4A	F5B	F5A	F6B	F6A	F7B	F7A
0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

S4	S3	S2	S1	R1	R6B	R6A	R2	R4	R5	R7	R8	●	R12	R10	R11
0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

S11	M8	M7	M6	M1	M5	M4	M3	M2	S10	S9	S8	S7	R3	S6	S5
0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

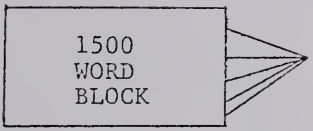
F0F	F0C	E2	E1	●	F0A	F0B	F4D	F4C	F4F	F4E	F1E	F1C	F0E	F0D	E3
0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

Figure 33. Scheme Used for Assignment of Field Sensor Channels to Input Hardware Buffer Words in the Tampa Green Band System

Raytheon hardware. The use of 61 field sensors, therefore, resulted in a utilization of all but three of the 64 available data bits in these words. Assignments of Tampa sensor functions to the various input word bit locations were made to correspond to their Woburn site counterparts whenever possible, minimizing the need for software changes in the control program to process differing bit locations for the same purpose. As the data logging program processed input bits in groups of 16-bit words, the sensor locations within each word with respect to data logging were not an important consideration.

The evaluation plan called for the processing of a considerable amount of on-line control system operating data, so considerable attention was paid to the question of an efficient data recording scheme to be used with the operating green band control system. This work resulted in the design of an entirely new data logging concept from that used in the Woburn system. This new technique also scans sensor inputs at a rate of 500 times per second and tests input words individually for changes from the values read at the last sensor scan. However, when changes are detected in the Tampa system, the individual bits comprising the word are tested against their previous values, and in the case of a single sensor bit changing status in a given sensor scan, only one word of information is written to the tape, as opposed to the five-word block comprising the four sensor words and a time value used in the Woburn system.

A format of this sensor data change word used in the data logging system is outlined in Figure 34, which also represents other elements of the data logging scheme adopted for the Tampa system. The Raytheon 704 computer used in the Tampa Green Band System allows word or byte addressing, and thus the four 16-bit sensor words mentioned above can be considered as consisting of eight 8-bit sensor bytes which are coded as bytes 0-7. Then, the sensor data change word written to the tape consists of (1) a 4-bit code containing the coded number of the sensor byte containing the bit or bits which changed data in the last tape scanning period, (2) 4 bits representing the number of 2-millisecond clock intervals that have occurred since the last sensor timing, and (3) 8 bits of data giving the sensor byte contents which have been detected as being different from their previous values. The use of four bits of time information in the sensor data change word presented a problem as the maximum time interval that could be represented in this scheme is $2^4 \times 0.002 = 32$ milliseconds. To handle this restriction, another type of tape data word was used to mark 4-bit clock overflows. This word consisted of a 4-bit code and the remaining 12 bits of the



VARIABLE POSITIONING OF DATA ITEMS WITHIN EACH BLOCK WRITTEN TO TAPE

DATA CODE	DATA ITEM	DATA STRUCTURE
0-7	SENSOR DATA CHANGE	1 WORD(4 TIME BITS, 4 CODE BITS, 8 DATA BITS)
8	TELETYPE MESSAGE	37 WORDS(4 CODE BITS AND 12 UNUSED BITS IN FIRST WORD, 72 8-BIT CHARACTERS IN THE REMAINING 36 WORDS)
10	DATA LOGGING END BLOCK	1 WORD(4 CODE BITS, 12 UNUSED BITS)
12	DRIVER DISPLAY EVENT	15 WORDS(4 CODE BITS AND 12 UNUSED BITS IN FIRST WORD. 10 WORDS OF GREEN BAND BULB STATUS, 4 WORDS OF SYSTEM STATUS DATA)
15	CLOCK OVERFLOW WORD	1 WORD(4 CODE BITS AND 12 HI-ORDER TIME BITS)

Figure 34. Data Logging Routine Tape Block Format for the Tampa Green Band System

16-bit system time word not represented in the individual sensor data change words previously discussed.

Provisions were also made to record driver display data from the field consisting of the status of the 152 bits controlling the green band bulbs and of the control bits for the ramp signs in a fashion similar to the Woburn system operation. In the Tampa system, these driver display data are recorded at a fixed rate of four times per second, representing a departure from the Woburn system concept, which stored such data asynchronously in time after a fixed number of sensor word groups. The use of a fixed recording rate for driver display data allows a higher degree of consistency in processing these data off-line than was possible with the other approach. The driver display output data format to the tape is shown in Figure 34, and uses a total of 15 words of data for each display record.

Another significant difference from the Woburn system data logging capability is supported in the Tampa data logging routines, and consists of a provision for typing alphanumeric data into the teletype keyboard while the data logger program is active, and then having this information transferred to the data tape in the form of a coded string of binary numbers. This allows a capability for run identification data to be stored on the tape with the corresponding study data. Operator comments concerning conditions detected in the operation of the system may also be entered, and all messages detected on the study tapes as printed by the off-line data analysis program with the study outputs to give a capability for the identification of the existence of unexpected operating conditions. Buffer storage in the on-line control program is provided to hold a 72-character comment, as this represents the usable line length on the teletype printer. If this is not sufficient to hold the amount of descriptive information the system operator needs to enter, additional lines of data may be typed in succession, each restricted to the 72-character limit.

The data logging program is configured to remain inactive until a teletype message has been received after data logging has been enabled through a sense switch on the computer control panel. This feature was used to allow studies to be started at specified points in time to provide a capability for replicating the timing of data sampling periods. The requirement to enter a teletype message before data logging can begin has the effect of requiring the system operator to enter study identification data on the tape file at the beginning of each study, facilitating an automatic tape data identification system.

As indicated in Figure 34, data for eventual tape storage is routed by the on-line program into one of two 1500-word storage buffers in core (recall that the Woburn system used two 140-word buffers for this purpose). The decision to use larger data buffers for this function in Tampa was based on considerations of how the data are transferred to tape in the recording process. Each time a completed data block is to be written to the tape, the tape drive control unit must first be instructed to get the tape moving at the proper recording speed. Then, data words are sent to the tape control unit "one-at-a-time," using program interrupts generated by the tape control unit when each word has been recorded to initiate the transfer of the next successive word from the buffer in core. When all words in the output buffer have been recorded, the tape control unit must be instructed to write an inter-record gap on the tape and then to stop the tape motion. As the operations associated with starting and stopping the tape require relatively long periods of time with respect to the time required to actually write data once the tape is moving, the use of smaller data buffers can greatly increase the computing workloads associated with data logging operations. Of greater importance, however, is the fact that the use of tape buffers which are too small can introduce the strong possibility of missing data, as the core buffer currently being used to hold process in such cases may be filled to capacity while the previous buffer is still being written to the tape.

When one of the Tampa data buffers is full, it is written on tape in the form of a 3,000-byte data block, and the other buffer is selected to hold the process data as they arrive. Exact recording rates vary with changing traffic conditions on the freeway and ramp, but each block of data written to the tape typically represents on the order of one-half minute of system operation. As the tape is written at a density of 800 8-bit bytes to the inch, a 3,000-byte buffer of tape data occupies less than four inches of storage space on the tape. Then, assuming an inter-record gap spacing between the data blocks on the tape of 0.6 inches [90, pp. 5-110], this means that some 50 hours of operating data for the Tampa Green Band System may be stored on a single 2,400-foot data tape. In practice, data logging is done in periods of several hours to facilitate the statistical blocking of study data into representative cell values, and each tape represents several days of system activity.

Off-Line Data Analysis

As discussed earlier, the data tapes prepared by the on-line green band control system data logging program, contain data of three basic categories: (1) field sensor state changes and associated time information, (2) driver display information containing the status of all of the green band bulbs and field signs, and (3) teletype messages from the system operator generated during operations of the system. Special purpose software to read the data tapes generated by the on-line control system and produce usable outputs was developed for the Tampa Green Band System, and is denoted by the acronym TOGAP, representing Tampa Operational Green Band Analysis Program. Figure 35 shows the internal structure of TOGAP, which consists of a main routine and 23 subroutines whose individual functions with respect to the computation of system performance indices will be discussed later in this chapter after a general overview of the operation of TOGAP. A listing of the program, which is coded in the FORTRAN IV computer language, may be found in Appendix A. Program development and production runs were conducted on an IBM System/370-165 computer located at the Northeast Regional Data Center of the State University System of Florida on the Gainesville campus of the University of Florida.

The MAIN routine reads run description cards, prints and punches output headings and calls on subroutine TIMID to process the data from the on-line tapes. A variety of output options are available, including a detailed analysis of vehicle trajectories through the ramp and freeway system.

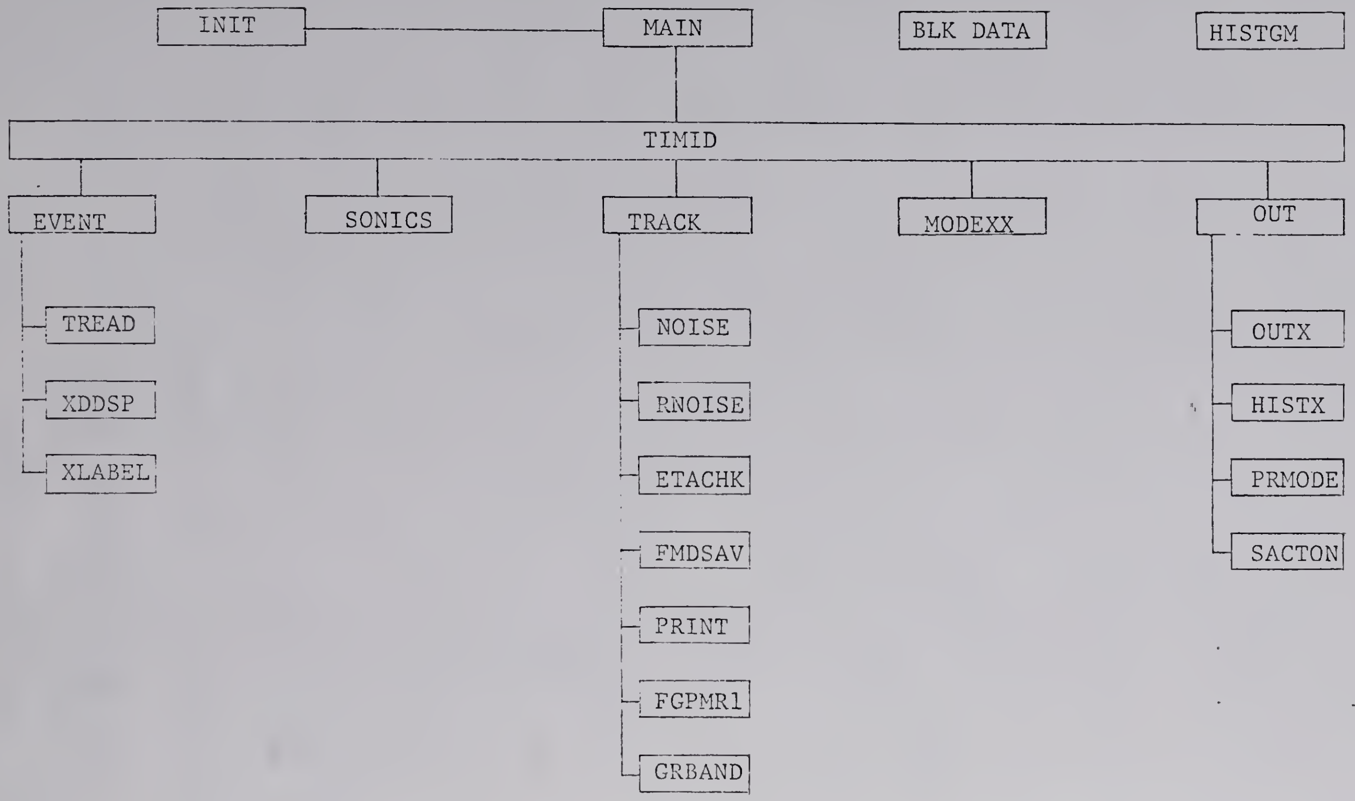


Figure 35. Subroutine Structure for TOGAP Data Reduction Software

Other operating options include provisions for punching data on merging vehicle arrival times at sensor locations in the merge area, which can then be used for subsequent gap availability, gap acceptance and gap rejection studies, and output containing sensor information available to the on-line control system for use in generating green bands. The use of the latter type of information will be described later in Chapter 5 when the development of a green band control program simulation model is discussed. Another option controlled by variables read by the main program is the use of the TOGAP system for the analysis of both before and after data tapes generated by the Tampa system. The Raytheon analysis software for the Woburn site included separate programs for the three cases of no control system in operation, Pacer system in operation, and green band system in operation [80].

Subroutine TIMID schedules data tape processing for each case requested, and calls for summary output at the end of the time period specified for the study. TIMID calls subroutine EVENT to read and decode data tapes. Each time a sensor event is detected, which is defined as a vehicle reported entering or leaving a loop sensor, subroutine TRACK is called to process the event and to perform vehicle tracking, which consists of identifying individual vehicles within the system as they pass through various freeway or ramp sensor sequences.

Subroutine TRACK calls on a number of support routines to collect the operating data on vehicle behavior within the system. Routines RNOISE and NOISE, for the computation of ramp vehicle acceleration noise and freeway vehicle acceleration noise, respectively, are provided. A routine named ETACHK is used to punch a card containing data passed to the master control routine green band system by the highway vehicle processor each time a new freeway vehicle ETA at the merge point is available. Subroutine FMDSAV is used to maintain a table of current freeway vehicle arrival times at the merge point for use in gap projection analysis. Subroutine GRBAND is called by TRACK to analyze ramp vehicle movement with respect to the green band display element.

Additional subroutines in the TOGAP system include subroutine SONICS, which processes information obtained from the modified sonic detectors located along the acceleration lane guard rail, and subroutine MODEXX, which performs an analysis of system modal behavior in the on-line control program. In addition, subroutine OUT is called by TIMID at the end of each tape run to generate statistical output information on the system performance during the course of the run.

Vehicle Identification and Tracking in TOGAP

The basic purpose of the TOGAP program is to transform magnetic tape data generated by vehicle actuations of field sensors into useful data on system performance. Figure 36 shows representative field sensor data after processing from the on-line data tapes by subroutine EVENT. The entries in the computer table represented in the output are, respectively, the table row number of the event, the input channel of the particular sensor (a driver display event is assigned to Channel No. 65), indication of the sensor event status (1 if the sensor came on, 0 if the sensor went off), the time of the sensor event, and the sensor channel name. In addition, the driver display events are printed with information on the status of the 152 bulbs comprising the green band display in the field, and information on the status of the various ramp signs, as well as the current values in the on-line control system for merge velocity, VMRG, three-minute freeway velocity average, VBAR, and the three-minute freeway volume count downstream of the merge area, Q. In addition, the printout for the driver display includes the information on the current control system mode obtained at the last update. Also, the variable GBMSK is printed, which is the variable used in the on-line control program to initiate a green band masking in response to ramp congestion.

```
TAPE = TOGM31, AUG 9, 1974,  7:15 AM  (1 WEEK AFTER OPENING)

-----------------------------------------------------------------------------
AT CLOCK =      0.0  . THE FOLLOWING TELETYPE MESSAGE WAS WRITTEN...
RUN 1  TOGM31  8-9-74  0715
-----------------------------------------------------------------------------


    IETRCW     CLOCK KFULL KFINI KRINHB
      473     16.960     0     0      1

   1 57.   1.       0.044 F4-C
   2 65.   1.       0.064 DDSP   11111111111111111111111111111111111111111111111111111111111111111111111111111000
                                 00000000000000000000000000000000000000000000000000000000000000000000000000000000
                                 MWC   DBGB    PTS    RED  AMBER  GREEN   VMRG   VBAR      Q   MODE GBMASK
                                   0      1      0      0      0      1     66     76     54      3      0

   3 17.   1.       0.118 S4
   4 45.   1.       0.124 S7
   5 45.   0.       0.172 S7
   6 17.   0.       0.184 S4
   7 56.   1.       0.284 F4-D
   8 57.   0.       0.296 F4-C
   9 44.   1.       0.442 S8
  10 40.   1.       0.472 M3
  11 19.   1.       0.476 S2
  12 48.   1.       0.488 S5
  13 44.   0.       0.514 S8
  14 48.   0.       0.520 S5
  15 19.   0.       0.520 S2
  16 38.   1.       0.522 M5
  17 56.   0.       0.530 F4-D
  18 65.   1.       0.576 DDSP   11111111111111111111111111111111111111111111111111111111111111111111111111111111
                                 11100000000000000000000000000000000000000000000000000000000000000000000000000000
                                 MWC   DBGB    PTS    RED  AMBER  GREEN   VMRG   VBAR      Q   MODE GBMASK
                                   0      1      0      0      0      1     66     75     54      3      0

  19  4.   1.       0.614 F1-A
  20  6.   1.       0.664 F2-A
  21 18.   1.       0.698 S3
  22 18.   0.       0.770 S3
  23 18.   1.       0.864 S3
  24  3.   1.       0.888 F1-B
  25  5.   1.       0.914 F2-B
  26 18.   0.       0.938 S3
  27  4.   0.       0.988 F1-A
  28  6.   0.       1.010 F2-A
  29 39.   1.       1.032 M4
  30 18.   1.       1.032 S3
  31 59.   1.       1.074 F4-E
  32 65.   1.       1.088 DDSP   11111111111111111111111111111111111111111111111111111111111111111111111111111111
                                 11111111110000000000000000000000000000000000000000000000000000000000000000000000
                                 MWC   DBGB    PTS    RED  AMBER  GREEN   VMRG   VBAR      Q   MODE GBMASK
                                   0      1      0      0      0      1     66     75     54      3      0
```

Figure 36. Output from Subroutine EVENT Showing Decoded Teletype Message, Field Sensor Activity, and Driver Display Data

As indicated earlier, the main routine calls on subroutine TIMID to analyze data tapes generated on-line, and TIMID calls subroutine EVENT to prepare tables such as represented in Figure 36. Each table represents the reduction of a single 3,000-byte tape record to event status data. Upon returning from EVENT, TIMID scans the prepared data table and identifies events in the table to schedule processing of the respective events. Subroutine MODEXX is called to update stored information on the status of the driver displays if a channel number of 65 is detected. Similarly, subroutine SONICS is called if the reported channel number of the current sensor actuation is that associated with one of the eleven sonic detectors along the guard rail of the merge area. If the next entry in the data table prepared by subroutine event is not a driver display event or a sonic detector event, subroutine TRACK is called to implement vehicle identification and tracking. Before the call to TRACK is made by subroutine TIMID, the channel number associated with the field sensor event is converted to an internal sensor code for use by TRACK. Table 5 shows these sensor codes for the Tampa system. The need for the conversion of input channel codes to sensor codes is related to the methods used for projecting vehicle movements from one sensor to another in the programs, as the processed data are held in FORTRAN arrays whose subscripts indicate the position

Table 5
Internal Sensor Code Assignments for TOGAP

CODE	SENSOR	TYPE	LOCATION
1 - 7	F7 - F1	Double-loop	I-75 outside lane upstream of merge area
8	R12	Single-loop	490 feet upstream of ramp entrance
9	R11	Single-loop	70 feet upstream of ramp entrance
10 - 13	R10 - R7	Single-loop	Initial section of ramp
14	R6B	Single-loop	Check-in detector at ramp traffic signal
15	R6A	Single-loop	Check-out detector at ramp traffic signal
16 - 20	R5 - R1	Single-loop	Final section of ramp
21 - 28	M1 - M8	Single-loop	Merge area
29 - 39	S1 - S11	Modified-sonic	Merge area guard rail
40	E3	Single-loop	Ashley Street ramp to I-75
41, 42	E1, E2	Single-loop	I-75 off-ramps near F5
43	F4C/F4d	Double-loop	I-75 center lane at F4
44	F4E/F4F	Double-loop	I-75 inside lane at F4
45	F1C	Single-loop	I-75 center lane at F1
46	F1E	Single-loop	I-75 inside lane at F1
47	F0A/F0B	Double-loop	I-75 outside downstream of merge area
48	F0C/F0D	Double-loop	I-75 center lane downstream of merge area
49	F0E/F0F	Double-loop	I-75 inside lane downstream of merge area

of the sensor in the system, and consecutive ordering of sensors in a given sequence is therefore needed to implement vehicle movements throughout the sequence.

Subroutine TRACK processes all sensor events in the system not related to sonic detector actuations or field display activity. Upon entry, a transfer is made to one of six sections in the program representing, respectively, code for the following sensor event times:

1. Freeway vehicle arrival at the leading edge of a freeway sensor station (T3);
2. Freeway vehicle departure from the first loop of a freeway sensor station (T4);
3. Freeway vehicle arrival at the second loop in a freeway sensor station (T1);
4. Freeway vehicle departure from the second loop in a freeway sensor station (T2);
5. Vehicle arrival at a single-loop detector leading edge (TIN);
6. Vehicle departure from the trailing edge of a single-loop presence detector (TOUT).

The processing done by TRACK is reviewed below for each of these cases.

At a T3 event, the sensor number is checked to see if the event represents a new vehicle arrival at the most distant upstream freeway sensor, F7. If in fact a new vehicle has been detected at this location, the count of vehicle identification numbers which have been assigned previously is incremented by 1 and the resulting number is assigned as the identification number which will be associated with this vehicle as it passes through the remaining sensors. Similarly, if a vehicle is detected at any of the downstream sensor stations at a T3 event which has not been expected at this time, a "cut-in" is claimed for the vehicle, and a new vehicle number is similarly assigned. Assuming, however, that the vehicle associated with the current T3 event is not associated with a new entry to the system, the time of vehicle arrival at the sensor is checked to see if it is within the time of arrival at this sensor predicted as a result of its detection at the previous upstream sensor. If the time of arrival of the vehicle in question is greater than that predicted at the previous sensor with a given tolerance, a "cut-out" is claimed and the vehicle is removed from the sensor lists established for it earlier. If the T3 event is identified as being associated with a vehicle moving through the system within the projected trajectory values, the vehicle parameters are removed from the previous sensor list and projected ahead to the next downstream sensor. Control is then returned to subroutine TIMID to process the next sensor event.

At a T4 event, representing a freeway vehicle departure from the first loop within a sensor station, the time of the vehicle passage from the sensor is recorded and control is returned to subroutine TIMID. No subsequent use of the T4 time information is made in the analysis programs, but it is included to provide a full capability for providing sensor timing reports if the vehicle tracking print option is selected.

At a T1 event, representing a freeway vehicle arrival at the second loop of a freeway sensor station, the velocity and acceleration of the current freeway vehicle are computed, using the following expressions:

$$\mathrm{VEL}(I,J) = \mathrm{GAGE}\ (I)/(\mathrm{T1}(I,J) - \mathrm{T3}\ (I,J)$$

$$\mathrm{ACC}(I,J) = (\mathrm{VEL}\ (I,J) - \mathrm{PV}\ (I,J))/(\mathrm{T3}(I,J) - \mathrm{PT}(I,J))$$

where I = sensor number on freeway or ramp,

J = vehicle track number,

GAGE(I) = distance from leading edge of first loop to leading edge of second loop for sensor I (nominally 20 feet), VEL(I,J) = velocity of the Jth vehicle in the Ith sensor,

ACC(I,J) = acceleration of the Jth vehicle in the Ith sensor,

T1(I,J) = T1 time of the Jth vehicle in the Ith sensor,

T3(I,J) = T3 time of the Jth vehicle in the Ith sensor,

PV(I,J) = velocity at the previous sensor of the Jth vehicle in the Ith sensor,

and PT(I,J) = time at the previous sensor of the Jth vehicle in the Ith sensor.

In addition to the velocity and acceleration and computations made at the T1 time outlined above, the estimated times of arrival for the current vehicle at the next sensor and at the merge point are then computed by the following equations:

$$\mathrm{ETANO}(I,J) = \mathrm{T3}(I,J) + \mathrm{DM}(I)/V(I,J)$$

$$\mathrm{ETA}(I,J) = \mathrm{T3}(I,J) + \mathrm{DS}(I)/V(I,J)$$

where DM(I) = distance fron sensor I to sensor I + 1

and DS(I) = distance from sensor I to merge point.

In addition to the processing done above, each time a new freeway vehicle velocity measurement is available subroutine NOISE is called to accumulate freeway vehicle acceleration noise data, and its operation will be discussed later.

At a T2 event, representing a freeway vehicle departure from the second loop of a double-loop velocity sensor, the length of the current freeway vehicle is computed from the following expression:

$$LEN(I,J) = (T2(I,J) - T1(I,J)) * V(I,J) - W$$

where LEN(I,J) = length of Jth vehicle in the Ith sensor (feet),

and W = assumed width for second loop in a freeway sensor station (nominally 6 feet).

In addition to the length computations outlined above at a T2 event, the assembled set of information for the current freeway vehicle is printed, if this option has been selected. Figure 37 shows representative vehicle tracking as performed by the TOGAP system. The first column in the figure is the sensor number for the vehicle in question, and ranges from 1 to 7 for freeway sensors F7 to F1, respectively. It is difficult to follow the progress of individual freeway vehicles through the system from this

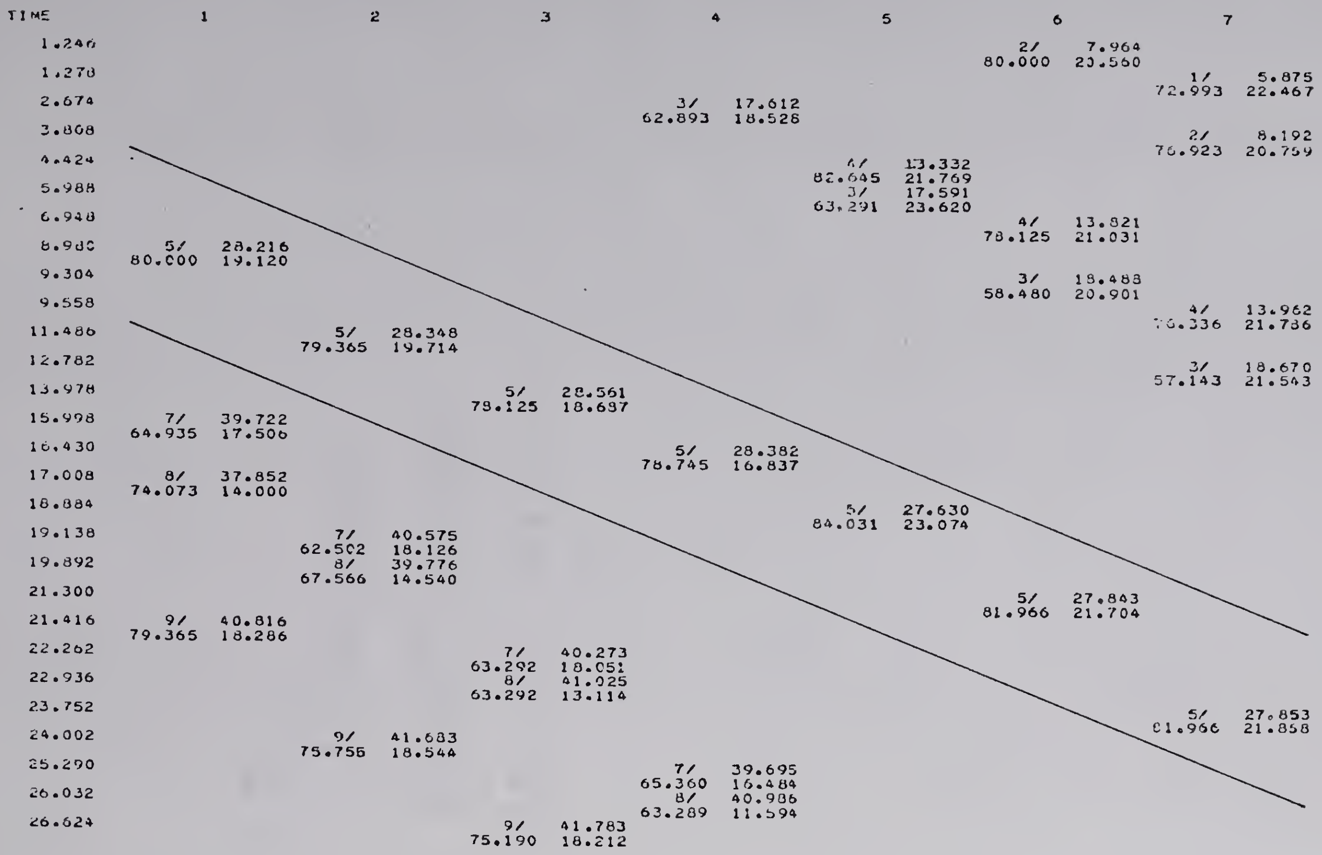
```
TAPE = TOGM31. AUG 9. 1974.  7:15 AM  (1 WEEK AFTER OPENING)

 I  J NE FJ CJ  W ST IN  CAR   DIST     T3        T4        T1       T2       VEL      LEN      ETA     ETA/MP    ACCEL
                                        MMON      0.064
CUTIN.  CAR     1   7    0.614
CUTIN.  CAR     2   6    0.664
 6  1  1  1  1  4  2  0    2  1000.    0.664     1.010     0.914    1.246   80.000   20.560    3.164    7.964    0.0
CUTOUT. CAR     1   7    1.278
 7  1  0  1  1  4  2  0    1  1200.    0.614     0.988     0.888    1.278   72.993   22.467    3.354    5.875    0.0
CUTIN.  CAR     3   4    1.966
 4  1  1  1  1  4  2  0    3   600.    1.966     2.298     2.284    2.674   62.893   18.528    5.146   17.612    0.0
CUTOUT. CAR     2   7    3.808
 7  2  0  1  2  4  1  0    2  1200.    3.200     3.544     3.460    3.809   76.923   20.769    5.800    8.192   -1.213
CUTIN.  CAR     4   5    3.846
 5  1  1  1  1  4  2  0    4   800.    3.846     4.160     4.088    4.424   82.645   21.769    6.266   13.332    0.0
 5  2  2  1  2  4  1  0    3   800.    5.204     5.646     5.520    5.998   63.291   23.620    8.364   17.591    0.123
 6  2  1  2  2  4  1  0    4  1000.    6.346     6.704     6.502    6.948   78.125   21.031    8.906   13.821   -1.808
CUTIN.  CAR     5   1    8.416
 1  1  1  1  1  4  1  0    5     0.    8.416     8.726     8.666    8.980   80.000   19.120   10.916   28.216    0.0
 6  3  1  3  3  4  1  0    3  1000.    8.502     8.980     8.844    9.304   58.480   20.901   11.922   18.488   -1.459
CUTOUT. CAR     4   7    9.558
 7  3  0  1  3  4  1  0    4  1200.    8.932     9.292     9.194    9.558   76.336   21.786   11.552   13.962   -0.692
 2  1  1  1  1  4  1  0    5   200.   10.910    11.232    11.162   11.486   79.365   19.714   13.430   28.348   -0.255
CUTOUT. CAR     3   7   12.782
 7  4  0  1  4  4  1  0    3  1200.   11.950    12.430    12.300   12.782   57.143   21.543   15.450   18.670   -0.388
 3  1  1  1  1  4  1  0    5   400.   13.406    13.730    13.662   13.978   78.125   18.687   15.960   28.561   -0,497
1ST VEH AT R10 =     6. AT TIME =     14.586
CUTIN.  CAR     7   1   15.328
 1  2  1  2  2  4  1  0    7     0.   15.328    15.682    15.636   15.998   64.935   17.506   18.408   29.722    0.0
 4  2  1  2  2  4  1  0    5   600.   15.886    16.186    16.140   16.430   78.745   16.837   18.426   25.382    0.250
CUTIN.  CAR     8   1   16.468
 1  3  2  2  3  4  1  0    8     0.   16.468    16.730    16.738   17.008   74.073   14.000   19.168   37.652    0.0
 5  3  1  3  3  4  1  0    5   800.   18.300    18.634    18.538   18.884   84.031   23.074   20.680   27.630    2.130
 2  2  1  2  2  4  1  0    7   200.   18.432    18.818    18.752   19.138   62.502   18.126   21.632   40.575   -0.784
 2  3  2  2  3  4  1  0    8   200.   19.292    19.590    19.588   19.892   67.566   14.540   22.252   39.776   -2.304
CUTIN.  CAR     9   1   20.658
 6  4  1  4  4  4  1  0    5  1000.   20.718    21.068    20.962   21.300   81.966   21.704   23.158   27.843   -0.654
 1  4  1  4  4  4  1  0    9     0.   20.858    21.162    21.110   21.416   79.365   18.286   23.378   40.816    0.0
 3  2  1  2  2  4  1  0    7   400.   21.566    21.956    21.882   22.262   63.292   18.051   24.726   40.273    0.252
 3  3  2  2  3  4  1  0    8   400.   22.318    22.632    22.634   22.935   63.292   13.114   25.478   41.025   -1.412
CUTOUT. CAR     5   7   23.752
 7  5  0  1  5  4  1  0    5  1200.   23.168    23.508    23.412   23.752   81.966   21.868   25.608   27.853    0.0
 2  4  1  4  4  4  1  0    9   200.   23.414    23.736    23.678   24.002   75.755   18.544   26.054   41.683   -1.412
 4  3  1  3  3  4  1  0    7   600.   24.640    24.968    24.946   25.290   65.360   16.484   27.700   39.695    0.672
 4  4  2  3  4  4  1  0    8   600.   25.438    25.726    25.754   26.032   53.289   11.594   28.598   40.986   -0.001
 3  4  1  4  4  4  1  0    9   400.   26.036    26.364    26.302   26.624   75.190   18.212   28.696   41.783   -0.215
CUTIN.  CAR    10   1   27.426
 1  5  1  5  5  4  1  0   10     0.   27.426    27.722    27.690   27.990   75.760   16.728   30.066   48.334    0.0
 5  4  1  4  4  4  1  0    7   800.   27.560    27.946    27.840   28.244   71.429   22.857   30.360   38.536    2.079
 5  5  2  4  5  4  1  0    8   800.   28.460    28.790    28.756   29.100   57.565   17.242   31.420   40.063    1.415
 4  5  1  5  5  4  1  0    9   600.   28.640    28.942    28.906   29.206   75.186   16.556   31.300   41.727   -0.002
 2  5  1  5  5  4  1  0   10   200.   30.054    30.362    30.318   30.628   75.755   17.484   32.694   46.323   -0.002
 6  5  1  5  5  4  1  0    7  1000.   30.432    30.834    30.720   31.110   69.446   21.084   33.312   38.841   -0.690
 •  6  1  6  6  4  1  0    9   800.   31.196    31.544    31.448   31.810   79.365   22.731   33.716   41.074    1.635
 6  6  2  5  6  4  1  0    8  1000.   31.434    31.776    31.732   32.062   67.113   16.147   34.414   40.136   -0.152
 3  5  1  5  5  4  1  0   10   400.   32.676    32.954    32.942   33.242   75.190   16.557   35.336   48.423   -0.215
```

Figure 37. Freeway Vehicle Tracking Output from TOGAP

tabular output, and a different method of displaying essentially the same information was developed, as represented in Figure 38. In this latter approach, vehicles are printed at a horizontal spacing on the output page corresponding to their position in the upstream freeway area, and their progress through the various freeway stations may be easily noted. Consider, for example, the progress through the system of Vehicle No. 5, which was first observed at sensor 1 at a time 8.980 seconds into the run. The information displayed for each vehicle at each freeway station consists of the vehicle number and estimated time of arrival at the merge point on the first line of station output, and the vehicle velocity and length (in feet) on the second line of each station output. Note the changes in these parameters as Vehicle 5 proceeds through the system. These changes have important implications to the operation of the on-line green band control program, and their effects will be reviewed in greater detail in Chapter 5.

Subroutine TRACK also processes the information from single-loop detectors installed on the freeway and ramp in much the same manner as it does from the double- loop detectors, with several significant differences. At a TIN event, the time of loop activation is recorded for occupancy calculations to be performed when the vehicle leaves the loop.



```
       TIME            1               2               3               4               5               6               7
         1.246                                                                                  2/    7.964
                                                                                             80.000  23.560
         1.278                                                                                                  1/    5.875
                                                                                                             72.993  22.467
         2.674                                                    3/   17.612
                                                               62.893  18.528
         3.808                                                                                                  2/    8.192
                                                                                                             76.923  20.759
         4.424                                                                    4/   13.332
                                                                               82.645  21.769
         5.988                                                                    3/   17.591
                                                                               63.291  23.620
         6.948                                                                                  4/   13.821
                                                                                             78.125  21.031
         8.980      5/   28.216
                 80.000  19.120
         9.304                                                                                  3/   18.488
                                                                                             58.480  20.901
         9.558                                                                                                  4/   13.962
                                                                                                             76.336  21.786
        11.486                      5/   28.348
                                 79.365  19.714
        12.782                                                                                                  3/   18.670
                                                                                                             57.143  21.543
        13.978                                      5/   28.561
                                                 78.125  18.697
        15.998      7/   39.722
                 64.935  17.506
        16.430                                                    5/   28.382
                                                               78.745  16.837
        17.008      8/   37.852
                 74.073  14.000
        18.884                                                                    5/   27.630
                                                                               84.031  23.074
        19.138                      7/   40.575
                                 62.502  18.126
        19.892                      8/   39.776
                                 67.566  14.540
        21.300                                                                                  5/   27.843
                                                                                             81.966  21.704
        21.416      9/   40.816
                 79.365  18.286
        22.262                                      7/   40.273
                                                 63.292  18.051
        22.936                                      8/   41.025
                                                 63.292  13.114
        23.752                                                                                                  5/   27.853
                                                                                                             81.966  21.858
        24.002                      9/   41.683
                                 75.756  18.544
        25.290                                                    7/   39.695
                                                               65.360  16.484
        26.032                                                    8/   40.986
                                                               63.289  11.594
        26.624                                      9/   41.783
                                                 75.190  18.212
```

Figure 38. Freeway Vehicle Trajectories by Vehicle Number

Also, the velocity of the vehicle at the current sensor is computed from the following expression:

V(I,J) = (DIST(I) - DIST(I-1))/(T3(I,J) - PT (I,J))

where DIST(I) = distance from first sensor on ramp or freeway to sensor I,

and DIST(I-1) = distance from first sensor on ramp or freeway to sensor (I-1).

Note that the computation of vehicle velocities from single-loop sensors is done by essentially using pairs of the single-loop sensors in a similar fashion to the closely spaced sensors in the double-loop detectors on the freeway. Velocity estimation using a single-loop sensor is possible by assuming an average vehicle length, but substantial errors can be introduced into the measurement process using this approach [74]. Acceleration measures are also computed for vehicles on the controlled section of the ramp, representing sensors R10 through R1, respectively. This computation is done using the following expression:

ACC(I,J) = (V(I,J) - PV(I,J))/T3(I,J) - PT(I,J))

Other processing is done for loop detector actuations in the ramp area, including green band tracking, merging gap predictions, and ramp acceleration noise computations. These functions will be discussed in the section on ramp operations analysis.

At a TOUT event, representing a vehicle departure from the trailing edge of a single loop sensor, the occupancy time of the sensor is updated using the following expression:

$$\mathrm{TOCC(I)} = \mathrm{TOCC(I)} + (\mathrm{TOUT(I)}-\mathrm{TIN(I)})$$

where: TOCC(I) = total time loop sensor I has been activated,

TOUT(I) = time of last vehicle departure from loop sensor I,

and TIN(I) = time of last vehicle arrival at loop sensor I.

Much of the vehicle tracking logic used in subroutine TRACK is based on the scheme used in the analysis software for the Woburn Green Band System developed by Raytheon [80], but substantial modifications were necessary to implement the use of the single loop detectors used on the Tampa ramp for vehicle monitoring. As subroutine TRACK is called more frequently than any other routine in the TOGAP system, particular attention was given to making its operation efficient in terms of the computer processing required to perform each function. For example, all of the computational effort required at a given sensor location to handle special conditions such as new vehicle arrivals at F7 or R10 is concentrated into one section of code which is reached by a single condition test, as opposed to distributing the processing functions throughout the program, requiring additional series of tests to identify the need for the special processing.

Figure 39 shows a representative output report for sensor activity on a data tape file generated by the on-line control system. The information at the top of the figure represents freeway vehicle activity, including counts at each loop on the freeway, velocity means and standard deviations for each double-loop sensor, and percentage occupancy figures for the single-loop sensors on the freeway. In addition, the seven upstream stations are monitored for vehicle "cut-in" and "cut-out" activities and the total of such occurrences for each sensor are also printed. In this figure, summary information is also available on the sensors throughout the ramp portion of the system from R12 through R1, and M1 through M8, representing respectively the approach to the merge area, and the merge area sensors themselves. The figure also displays count data and occupancy values for the three evaluation loop sensors used in the system, E1, E2 and E3, respectively, and a count of the number of driver dis-

```
TEST 1      AFTER PROCESSING WITH FULL OUTPUT (NO PUNCH)  TOCM31/1

REPORT OF SENSOR CHANNEL ACTIVITIES...

----------------------------------------------------------------------------------------------------------------

                                             F4-E   F4-F                               F1-E          F0-E   F0-F
                                              216    220                                220           215    216
DATA ORGANIZATION                                 80.768                                                  83.928
VEL SENSOR NAME           PRES SENSOR NAME         6.335                                                   5.850
NLOOP1    NLOOP2               COUNT                                                  7.865
    VEL MEAN                   OCCUPANCY
    VEL STD                    VEL MEAN      F4-C   F4-D                               F1-C          F0-C   F0-D
                               VEL STD        247    257                                242           250    259
                                                  77.094                                                  79.588
                                                   7.787                                                   8.715
                                                                                      9.109

   F7-A   F7-B   F6-A   F6-B   F5-A   F5-B   F4-A   F4-B   F3-A   F3-B   F2-A   F2-B   F1-A   F1-B   F0-A   F0-B
    238    238    234    234    236    237    244    244    249    261    257    252    248    250    305    304
        73.058        71.542        70.649        72.578        77.638        74.683        73.291        65.104
         8.254         8.269         7.909         7.910         8.124         7.788         8.197         9.313
          238.            6.            6.           13.           14.           15.            3. CUTINS
            0.           10.            4.            5.            8.            7.          258. CUTOUTS
----------------------------------------------------------------------------------------------------------------

   S1     S2     S3     S4     S5     S6     S7     S8     S9     S10    S11
      3    295    256    298   1213    299    360    624    315    329    339
      2     54    151     54    928     54     95    386     23     12      1
    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
----------------------------------------------------------------------------------------------------------------

   M1     M2     M3     M4     M5     M6     M7     M8
     53     54     54     52     47     38     32     26
  6.967  7.253  7.764  7.555  6.598  5.174  3.946  2.506
 26.706 32.013 38.403 34.334 34.780 18.677 18.606 21.906
 14.132 17.472 13.926 18.433 15.892 20.689 20.986 22.425
     7.    13.    20.    19.    15.    10.     9.     8. CUTINS
     2.     4.     2.     1.     1.     5.     5.     8. CUTOUTS
----------------------------------------------------------------------------------------------------------------

   R12    R11    R10    R9     R8     R7     R6-B   R6-A   R5     R4     R3     R2     R1
     56     58     58     57     56     57     52     59     56     57     57     56     56
  2.817  3.186  3.822  4.063  9.113  7.013 16.076 10.288  2.643  3.778  3.632  3.538  3.873
 44.265 42.963 43.546 43.172 42.719 40.253 31.340 37.647 38.670 42.522 41.365 41.168 39.250
 12.245 23.314  4.093 12.131  9.440 11.068 16.818 12.635 31.313  9.923  7.793  8.231 10.427
     0.     0.    58.     0.     0.     3.     1.     8.     6.     8.     9.     8.     8. CUTINS
     0.     0.     0.     1.     1.     2.     3.     1.     1.     0.     0.     0.     0. CUTOUTS
----------------------------------------------------------------------------------------------------------------

   E1     E2     E3
      0      0     44
    0.0    0.0  2.820
----------------------------------------------------------------------------------------------------------------

  DOSP
  3504
----------------------------------------------------------------------------------------------------------------
```

Figure 39. Sensor Activity Summary from TOGAP

play events processed by the program in the previous run is also printed. As indicated earlier, this driver display information is generated by the system at a rate of approximately four events per second (actually, a new driver display datum is recorded every 0.256 seconds to agree with internal clock cycle detection logic operating at this rate).

Analysis of Freeway Operations

The computations for the individual freeway vehicle characteristics upstream of the merge area were reviewed in the previous section, and were derived from information recorded by the on-line control system from individual field sensor actuations. This information obtained in the earlier analysis must be considered from the standpoint of its ability to predict freeway system characteristics upstream of the merge area. One of the more significant of these measures is the acceleration noise associated with upstream freeway vehicles [38].

Acceleration noise, defined as the standard deviation of vehicle acceleration in a system, is dependent on three basic elements of the traffic stream flow: (1) the driver, (2) the roadway, and (3) existing traffic conditions. As discussed in Chapter 1, acceleration noise is a measure of the stability of flow in a given traffic stream, and high values for acceleration noise represent conditions of turbulent flow, while low values represent correspondingly, conditions of smooth flow. Acceleration noise in the Tampa system upstream of the merge area is computed from the following expression:

$$\sigma_k = \sqrt{\sum_{i=2}^{7} (a_{k,i} - \bar{a}_k)^2/6}$$

where σ_k = acceleration noise value for vehicle k (feet/second^2),

$a_{k,i}$ = acceleration for the kth vehicle between sensor stations (i-1) and (i),

$\bar{a}_k$ = average acceleration of vehicle k over its trajectory upstream of the merge area.

Note that there are seven freeway sensor stations. This means that six acceleration values can be used for each vehicle.

Detailed printout representing the acceleration noise values computed for each vehicle as it leaves the upstream section is available from TOGAP if requested, but a more meaningful use of this information is that shown in Figure 40, which represents a histogram of the individual observed values of acceleration noise for the vehicles in a given time span. Absolute values of the acceleration

```
        TEST 1       AFTER PROCESSING WITH FULL OUTPUT (NO PUNCH)  TOGM31/1


        DISTRIBUTION OF HIGHWAY ACCELERATION NOISE

NUMBER OF OBSERVATIONS =     255.
MAXIMUM VALUE OBSERVED =     0.613788E 01
MINIMUM VALUE OBSERVED =     0.0
MEAN VALUE OF DATA =     0.112068E 01
VARIANCE OF DATA =     0.402122E 00
STANDARD DEVIATION OF DATA =     0.634131E 00
HISTOGRAM CELL WIDTH =     0.100000E 00

---------------------------------------------------------------------------------------------------------
CLASS        | NUMBER | CUM        | CUM        | F R E Q U E N C Y   D I S T R I B U T I O N
UPPER        | IN     | TOTAL      | PER        |  (EACH STAR =          1.0 OBSERVATIONS)
LIMIT        | CLASS  | CASES      | CENT       |
---------------------------------------------------------------------------------------------------------
0.1000E 00|       15|         15|      5.88|***************
0.2000E 00|        0|         15|      5.88|
0.3000E 00|        1|         16|      6.27|*
0.4000E 00|        3|         19|      7.45|***
0.5000E 00|        6|         25|      9.80|******
0.6000E 00|        9|         34|     13.33|*********
0.7000E 00|       25|         59|     23.14|*************************
0.8000E 00|       31|         90|     35.29|*******************************
0.9000E 00|       31|        121|     47.45|*******************************
0.1000E 01|       19|        140|     54.90|*******************
0.1100E 01|       24|        164|     64.31|************************
0.1200E 01|       18|        182|     71.37|******************
0.1300E 01|       17|        199|     78.04|*****************
0.1400E 01|       10|        209|     81.96|**********
0.1500E 01|       12|        221|     86.67|************
0.1600E 01|       10|        231|     90.59|**********
0.1700E 01|        4|        235|     92.16|****
0.1800E 01|        3|        238|     93.33|***
0.1900E 01|        4|        242|     94.90|****
0.2000E 01|        4|        246|     96.47|****
0.2100E 01|        1|        247|     96.86|*
0.2200E 01|        0|        247|     96.86|
0.2300E 01|        1|        248|     97.25|*
0.2400E 01|        0|        248|     97.25|
0.2500E 01|        2|        250|     98.04|**
0.2600E 01|        0|        250|     98.04|
0.2700E 01|        1|        251|     98.43|*
0.2800E 01|        0|        251|     98.43|
0.2900E 01|        0|        251|     98.43|
0.3000E 01|        1|        252|     98.82|*
0.3100E 01|        0|        252|     98.82|
0.3200E 01|        0|        252|     98.82|
0.3300E 01|        0|        252|     98.82|
0.3400E 01|        0|        252|     98.82|
0.3500E 01|        0|        252|     98.82|
0.3600E 01|        0|        252|     98.82|
0.3700E 01|        0|        252|     98.82|
0.3800E 01|        1|        253|     99.22|*
0.3900E 01|        0|        253|     99.22|
0.4000E 01|        1|        254|     99.61|*
0.4100E 01|        0|        254|     99.61|
0.4200E 01|        0|        254|     99.61|
0.4300E 01|        0|        254|     99.61|
0.4400E 01|        0|        254|     99.61|
0.4500E 01|        0|        254|     99.61|
0.4600E 01|        0|        254|     99.61|
0.4700E 01|        0|        254|     99.61|
0.4800E 01|        0|        254|     99.61|
0.4900E 01|        0|        254|     99.61|
0.5000E 01|        0|        254|     99.61|
0.5100E 01|        1|        255|    100.00|*
```

Figure 40. Freeway Vehicle Acceleration NOISE Output from TOGAP

noise parameter have little significance, as any roadway section has associated with it a natural acceleration noise due to its construction features and average traffic flow characteristics. What is important, however, is the comparison of acceleration noise for a given section of roadway for differing operating conditions, such as those that will be present in the before and after operation of the Tampa moving merge control system. If the operation of the merge control system is such that it successfully assists the ramp merging operations with the freeway traffic, a reduction in the acceleration noise reported for freeway vehicles should be noted. Correspondingly, if the operation of merge control system introduces additional difficulties in the merging operation at the freeway entrance point, a corresponding increase in the value of measured acceleration noise would be expected. As the geometrics of the study section are fixed, and the characteristics of the driver population using the system will, on the average, not change during the study period, it is possible to assume that any variations in acceleration noise will be due to the traffic interactions in the system, allowing a measurement of the quantitative effect of the control system on freeway flow. Other system measures upstream of the freeway merging area that will be generated by the TOGAP system include observed vehicle velocity distributions across the various stations (see Figure 41), observed headway values (vehicle interarrival time values), and an analysis of freeway vehicle lane changing upstream of the merge area.

Analysis of Freeway Vehicle Lane Changing Upstream of the Merge Area

Since the green band system uses measured information on freeway gaps upstream of the merge area to project green bands to assist the merging maneuvers of ramp vehicles, consideration must be given to the frequency with which freeway vehicles enter and leave the outside lane upstream of the ramp. This is directly related to the stability of green bands displayed to ramp drivers. Although the Raytheon analysis software had a capability for analyzing vehicle cut-ins and cut-outs at upstream freeway sensors, the information was displayed in a tabular format which was difficult to analyze without extensive manual organization efforts. To alleviate this difficulty in the Tampa analysis software, a technique was developed to produce what is called a "vehicle persistence table" for the freeway vehicles upstream of the merge area, and representative output from this process is shown in the TOGAP output in Figure 42. The headings at the top of this table represent the seven sensor stations upstream of the ramp area, the numbers 1 through 7 being associated with freeway sensor stations F7 through F1 respectively, and the numbers down the left-hand side of the table represent these same freeway stations where vehicle de-

```
          TEST 1      AFTER PROCESSING WITH FULL OUTPUT (NO PUNCH)   TOGM31/1


                              DISTRIBUTION OF FWY VEH VELOCITIES AT F1

NUMBER OF OBSERVATIONS =     248.
MAXIMUM VALUE OBSERVED =     0.108701E 03
MINIMUM VALUE OBSERVED =     0.529113E 02
MEAN VALUE OF DATA =   0.732906E 02
VARIANCE OF DATA =   0.674656E 02
STANDARD DEVIATION OF DATA =    0.821374E 01
HISTOGRAM CELL WIDTH =    0.200000E 01

----------------------------------------------------------------------------------------------------------------------
CLASS          | NUMBER  | CUM          | CUM        |  F R E Q U E N C Y   D I S T R I B U T I O N
UPPER          | IN      | TOTAL        | PER        |   (EACH STAR =          1.0 OBSERVATIONS)
LIMIT          | CLASS   | CASES        | CENT       |
----------------------------------------------------------------------------------------------------------------------
0.2000E 01|          0|            0|      0.0 |
0.4000E 01|          0|            0|      0.0 |
0.6000E 01|          0|            0|      0.0 |
0.8000E 01|          0|            0|      0.0 |
0.1000E 02|          0|            0|      0.0 |
0.1200E 02|          0|            0|      0.0 |
0.1400E 02|          0|            0|      0.0 |
0.1600E 02|          0|            0|      0.0 |
0.1800E 02|          0|            0|      0.0 |
0.2000E 02|          0|            0|      0.0 |
0.2200E 02|          0|            0|      0.0 |
0.2400E 02|          0|            0|      0.0 |
0.2600E 02|          0|            0|      0.0 |
0.2800E 02|          0|            0|      0.0 |
0.3000E 02|          0|            0|      0.0 |
0.3200E 02|          0|            0|      0.0 |
0.3400E 02|          0|            0|      0.0 |
0.3600E 02|          0|            0|      0.0 |
0.3800E 02|          0|            0|      0.0 |
0.4000E 02|          0|            0|      0.0 |
0.4200E 02|          0|            0|      0.0 |
0.4400E 02|          0|            0|      0.0 |
0.4600E 02|          0|            0|      0.0 |
0.4800E 02|          0|            0|      0.0 |
0.5000E 02|          0|            0|      0.0 |
0.5200E 02|          1|            1|     0.40 |*
0.5400E 02|          4|            5|     2.02 |****
0.5600E 02|          4|            9|     3.63 |****
0.5800E 02|          1|           10|     4.03 |*
0.6000E 02|          5|           15|     6.05 |*****
0.6200E 02|          5|           20|     8.06 |*****
0.6400E 02|         14|           34|    13.71 |**************
0.6600E 02|         21|           55|    22.18 |*********************
0.6800E 02|         33|           88|    35.48 |*********************************
0.7000E 02|         31|          119|    47.98 |*******************************
0.7200E 02|         31|          150|    60.48 |*******************************
0.7400E 02|         23|          173|    69.76 |***********************
0.7600E 02|         10|          183|    73.79 |**********
0.7800E 02|         13|          196|    79.03 |*************
0.8000E 02|         16|          212|    85.48 |****************
0.8200E 02|         11|          223|    89.92 |***********
0.8400E 02|         10|          233|    93.95 |**********
0.8600E 02|          8|          241|    97.18 |********
0.8800E 02|          1|          242|    97.58 |*
0.9000E 02|          1|          243|    97.98 |*
0.9200E 02|          1|          244|    98.39 |*
0.9400E 02|          1|          245|    98.79 |*
0.9600E 02|          0|          245|    98.79 |
0.9800E 02|          1|          246|    99.19 |*
0.1000E 03|          0|          246|    99.19 |
0.1020E 03|          2|          248|   100.00 |**
```

Figure 41. Distribution of Freeway Vehicle Velocities at F1

```
TEST 1      AFTER PROCESSING WITH FULL OUTPUT (NO PUNCH)   TOGM31/1


VEHICLE PERSISTENCE TABLE...

                        ENTRY POINT
               1      2      3      4      5      6      7

          1   10
          2    5      0
          3    6      0      0
EXIT      4    3      0      0      3
POINT     5    3      0      0      0      4
          6    2      0      1      0      2      2
          7  208      6      6      9      8      8      3
```

Figure 42. TOGAP Output for the Analysis of Freeway Vehicle Lane Changing Upstream of the Merge Area

partures from the upstream sensor stations were noted. Thus, deviations from the expected freeway vehicle behavior, which is to enter at station 1 and leave at station 7, can be easily noted in the table. Note the data presented indicate that a majority of the freeway vehicles observed by the system for the particular period in the example did in fact follow the expected trajectory. There are a number of cut-outs, however, at the upstream stations, as represented by vehicle counts above the bottom row of the table. A substantial number of freeway vehicles are noted on the upper diagonal of the table, which represents vehicles that were detected at a single sensor station only and then not seen again by the analysis software. Upstream cut-ins and cut-outs can contribute significantly to the instability of the green band movements presented on the driver display, as will be discussed in Chapter 5, and this table provides an effective means of assessing this category of freeway vehicle behavior for before and after conditions relating to the merge system installation.

Consideration of the outputs of this program feature for data taken in the before studies supported a decision made earlier in the project to implement freeway markings along the inside of the freeway merging lane. This was accomplished by installing raised plastic reflectors at intervals of 50 feet along the lane boundary, and by painting a solid white stripe on the road surface in the same location.

Analysis of data taken after the markings were in place indicates a reduction in the frequency of lane changing in the upstream area, and this was the desired objective.

Analysis of Ramp Operations

One of the more significant ramp system performance measures for moving merge control systems is that of the ramp vehicle travel time through the ramp system, e.g., the time it takes for the ramp vehicles to move through the section of the ramp under control to the merge area. Figure 43 shows outputs from the TOGAP program giving this information in the form of a frequency histogram for the ramp vehicles observed in a representative study period. These data are derived by considering the arrival of the first vehicle at the initial ramp system sensor, R10, and storing this time of arrival in an array of ramp vehicle arrival times. Then, as this first ramp vehicle proceeds through the ramp, its arrival at the last ramp sensor is noted, and the arrival time used in conjunction with the previously stored input time to derive a "time-on-ramp" value. The anticipated effect of the operation of the green band control system on ramp vehicle travel times will be to shift the mean of the "before" distribution of vehicle travel times on the ramp to the mean green band traverse time across the ramp display. Thus, this phase of the evaluation will consist

```
          TAPE  = TOGM31, AUG 9, 1974,  7:15 AM   (1 WEEK AFTER OPENING)

          TRAVERSE TIME OF ALL RAMP VEHICLES BETWEEN R10 ENTRY AND R1  EXIT
NUMBER OF OBSERVATIONS =     25.
MAXIMUM VALUE OBSERVED =    0.230480E 02
MINIMUM VALUE OBSERVED =    0.961011E 01
MEAN VALUE OF DATA =    0.164151E 02
VARIANCE OF DATA =    0.111567E 02
STANDARD DEVIATION OF DATA =     0.334017E 01
HISTOGRAM CELL WIDTH =    0.500000E 01
-----------------------------------------------------------------------------------------
CLASS          | NUMBER | CUM        | CUM    |
UPPER          | IN     | TOTAL      | PER    |   F R E Q U E N C Y   D I S T R I B U T I O N
LIMIT          | CLASS  | CASES      | CENT   |    (EACH STAR =            1.0 OBSERVATIONS)
-----------------------------------------------------------------------------------------
0.50000E 01|         1|          1|    4.00|*
0.10000E 02|         7|          8|   32.00|*******
0.15000E 02|        13|         21|   84.00|*************
0.20000E 02|         4|         25|  100.00|****
REMAINING ENTRIES ARE ALL ZERO...
```

Figure 43. TOGAP Output Showing Distribution of Vehicle Travel Times on the Ashley Street Ramp

of comparisons of distributions of ramp travel times for the case of the control system in operation and the case of the control system not in operation (obtained from the several months of "before" data collection on the ramp). Ramp system performance evaluations will also include measures of performance similar to those used on the freeway, including measurements of inter-arrival time headways at R10 and R1, both for the stopped-modes of system operation and for the moving mode, and a distribution of ramp vehicle velocities across the various sensor locations. In addition, several performance measures relating specifically to the operation of the green band control system will be derived from data tapes generated on-line from the control system.

Ramp vehicle driver observance of the green band display is monitored by subroutine GRBAND. Figure 44 shows representative outputs from the green band tracking performed by the TOGAP system on data tapes. The tracking distance of each ramp vehicle from the leading edge of the green band guiding the vehicle is computed, and the relative velocity between each ramp vehicle and the green band opposite that vehicle is also available. In addition, the green band width versus the sensor location on the ramp for each vehicle is tabulated to give an indication of green band stability throughout the ramp display. Note that in Figure 44, the tracking distance of vehicles from the leading

```
TEST 1      AFTER PROCESSING WITH FULL OUTPUT (NO PUNCH)   TOGM31/1

SUMMARY OF  VEHICLE TRACKING AGAINST GB FIELD DISPLAY
                 R9        R8        R7        R6B       R6A       R5        R4        R3        R2


 TRACKING DISTANCE OF VEHICLE FROM LEADING EDGE OF GREEN BAND

MEAN MM    184.89    158.44    142.80    127.37    139.79    132.67     94.89     99.11     44.40
SIGMA      146.95    107.31    126.26    106.63    111.79     79.56     65.30     33.77     11.93
SUMSQ 0.100400000E 07   0.726656000E 06   0.608736000E 06   0.238832000E 06   0.422720000E 05
                0.659152000E 06   0.524272000E 06   0.430736000E 06   0.197344000E 06
COUNT            18.       18.       20.       19.       19.       16.       18.       18.       20.



MEAN SG                                                12.00    ******    ******    ******    ******
SIGMA                                                   0.0     ******    ******    ******    ******
SUMSQ                                      0.144000000E 03   0.0                         0.0
                                                        0.0                   0.0
COUNT                                                   1.        0.        0.        0.        0.


 RELATIVE VELOCITY BETWEEN VEHICLE AND GREEN BAND

MEAN MM    -1.14     -0.24      3.85     15.48      7.14      6.76     17.59     21.56     22.77
SIGMA       9.59      6.92      8.45     16.55     11.36     47.03     10.46      6.47      7.41
SUMSQ 0.167831880E 04   0.172306979E 04   0.342148901E 04   0.753553516E 04   0.114630391E 05
                0.852629150E 03   0.975435156E 04   0.466289219E 05   0.911875391E 04
COUNT            18.       18.       20.       19.       19.       18.       18.       18.       20.



MEAN SG                                               -16.63    ******    ******    ******    ******
SIGMA                                                   0.0     ******    ******    ******    ******
SUMSQ                                      0.276550547E 03   0.0                         0.0
                                                        0.0                   0.0
COUNT                                                   1.        0.        0.        0.        0.


 GREEN BAND WIDTH (FEET)

MEAN MM    224.00    240.67    262.80    275.58    274.32    299.11    306.89    278.22    239.80
SIGMA      139.07    114.33    127.69    118.45    137.57    137.06    153.17    150.96    167.82
SUMSQ 0.125129600E 07   0.170736000E 07   0.178932800E 07   0.211755200E 07   0.171336000E 07
                0.127764000E 07   0.170948800E 07   0.194857600E 07   0.180352000E 07
COUNT            18.       18.       20.       19.       19.       16.       18.       18.       20.
```

Figure 44. Summary Output from TOGAP Green Band/Ramp Vehicle Tracking

edge of the green band and the relative velocity of the difference between vehicles in the green band are represented for both modes of the system operation which generate green bands, e.g., for the stopped-gap mode (SG) and the moving mode (MM). A subroutine which did ramp vehicle tracking against green band positions for the Woburn system was adapted for use in the TOGAP software, but required extensive modifications to account for the use of single-loop presence sensors instead of double-loop sensors for data collection on the Tampa ramp, and the use of a variable green band speed in the Tampa moving mode operations, which necessitated the use of a table of prestored green band speed values versus ramp sensor numbers to give a true indication of the green band speed in any point along the display.

To give an indication of the system success rate for controlled merging in the operations of the Tampa system, coding was devised to calculate each of the various ramp sensors. A simple frequency definition of probability was used, as represented in the following expression:

$$P(\text{Ramp vehicle has a green band at ramp sensor } i) = \frac{NGB_i}{N_i}$$

where NGB_i = total number of vehicles at sensor i which had a valid green band indication,

and N_i = number of ramp vehicles crossing sensor i.

This expression is evaluated for each of the ramp sensors for both the moving modes and stopped-gap modes of operation during the course of each study period. A similar analysis is conducted for ramp activity at the sensor R3, which controls the YIELD sign. Here, the total count of vehicles crossing sensor R3 is maintained for the stopped-gap and moving modes of operation, and the count of YIELD sign activations for each case is maintained. Recall that the Tampa Green Band System has a mode of operation in which the bands displayed to the ramp are masked in response to merge area congestion, and under these conditions the yield sign is automatically turned on, requiring that separate counts be maintained of yield sign activations during the periods of system masking and the periods of normal system operation.

To provide some indication of the potential accident conflicts on the ramp associated with operation of moving merge control system, several techniques to predict these situations from observed sensor data were developed. To monitor driver observance of the traffic signal indication in the stopped-gap and stopped-metering modes of operation, logic was added to the ramp vehicle tracking section of subroutine TRACK which checks the condition of the ramp traffic light for each vehicle which is crossing the sensor immediately past the light; then, if the ramp traffic light is displaying a red indication and a sensor actuation is recorded for the check-out detector associated with light, a counter is incremented which gives the total number of stop light violations. In addition, ramp vehicle accelerations computed at each ramp sensor are checked to see if they exceed a deceleration rate of 8 feet/second^2, which is assumed to be representative of a vehicle maneuver having the potential of causing an accident involving the vehicle behind it on the ramp. A table of these deceleration conflicts at each ramp sensor is printed as a standard output in both before and after studies involving ramp operations. The expected result of the operation of the control system will be to reduce the number of these accident conflict situations observed on the ramp section under the control of the green band system.

Graphical Output of Ramp Vehicle and Green Band Interactions

Since one of the more important questions to be answered in the evaluation of moving merge control systems is the question of driver compliance with the various field displays, a method for depicting this interaction was coded in the TOGAP software. Representative output from this section of the program appears in Figure 45. Data presented in each line of this output are in order, the time at which the current green band display information was recorded, the

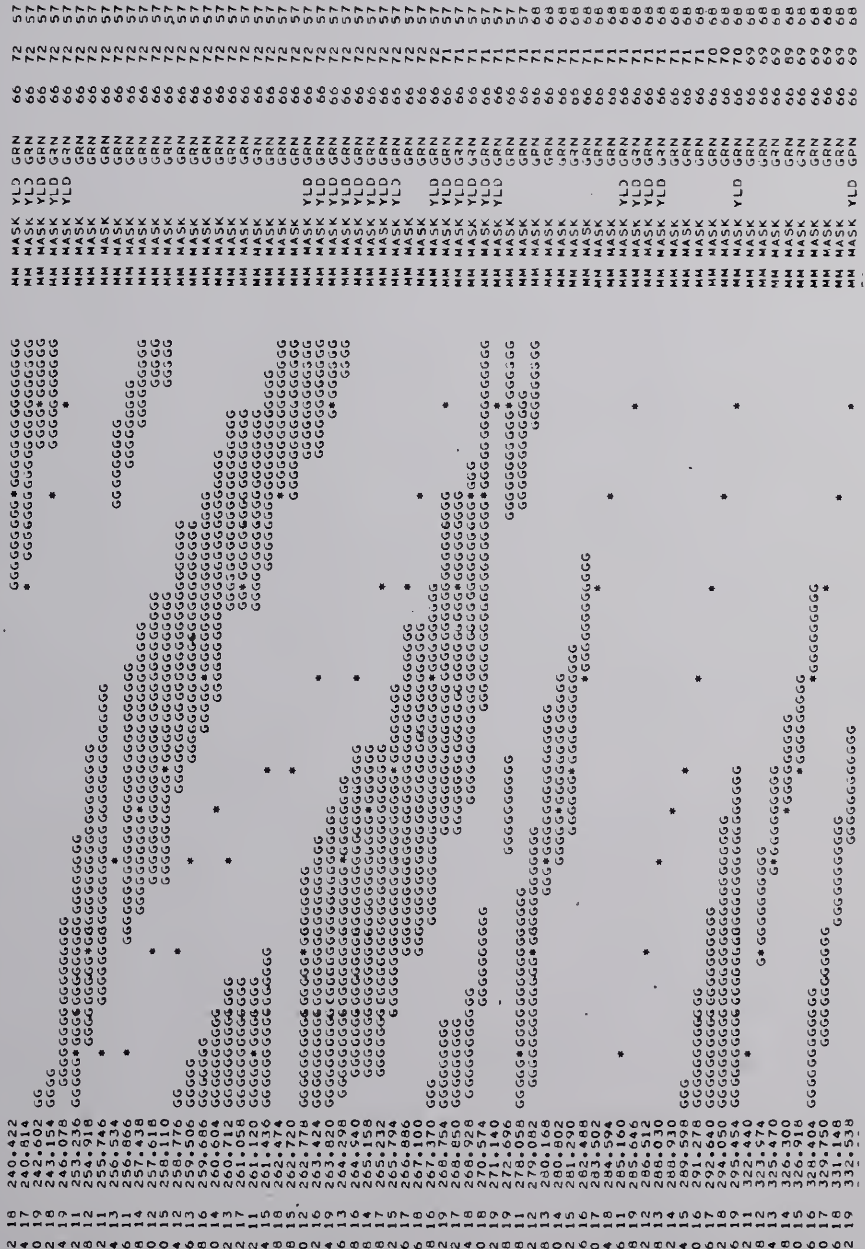


Figure 45. Pictorial Display of TOGAP Green Band/Ramp Vehicle Tracking

vehicle sensor number representing the current vehicle position on the ramp, the time at which the ramp vehicle was at the sensor, a series of "G" characters representing lighted eight-foot sections of the green band display, and a "*" character representing the position of the ramp vehicle with respect to the current position of the green band being currently displayed. Other data on each line represent the mode of the system (SG or MM, as discussed earlier), information on whether or not the green band system is currently masked, an indication of the yield sign activity, the current traffic signal indication, and numerical values for the current green band terminal speed, VMRG, three-minute freeway velocity average upstream from the entrance ramp, VBAR, and three-minute volume count downstream of the ramp merge area, Q. The sequence of green band versus vehicle outputs may be used to assess the degree of ramp vehicle driver compliance with the presented green bands. It should be noted that the output displayed in Figure 45 was obtained from a system data tape which was generated before the control program was given the capability of recording green band masking conditions, and thus the masking condition indicated in each line of the output is not representative of the actual system conditions (e.g., if the system is masked, no green bands are displayed to the field, and no strings of characters representing bands would be displayed during these period).

Use of Sonic Detectors for Lateral Vehicle Displacement Analysis

Modified sonic vehicle presence detectors were used to measure merge area vehicle displacements from the acceleration lane guard rail, allowing a capability for the prediction of the merge point location in actual system operation. Figure 46 shows data used for the calibration of the sonic detectors in the Tampa Green Band System. These data were obtained by manual observation of vehicle positions in the merging area in front of these detectors and correlated with observed sonic sensor pulse widths reported by the off-line analysis software. A regression model was fitted to the data, resulting in the following expression:

$$D = 39.931 - (521.55) \times DT,$$

where D = the displacement of the right hand side of the merging ramp vehicle from the sonic detector head (feet),

and DT = reported pulse width from the sonic sensor head for the vehicle in question (seconds).

As the width of the acceleration lane varied as a function of its length downstream along the freeway, some means of providing a common basis of comparison for ramp vehicle displacements was required. The technique was adopt-

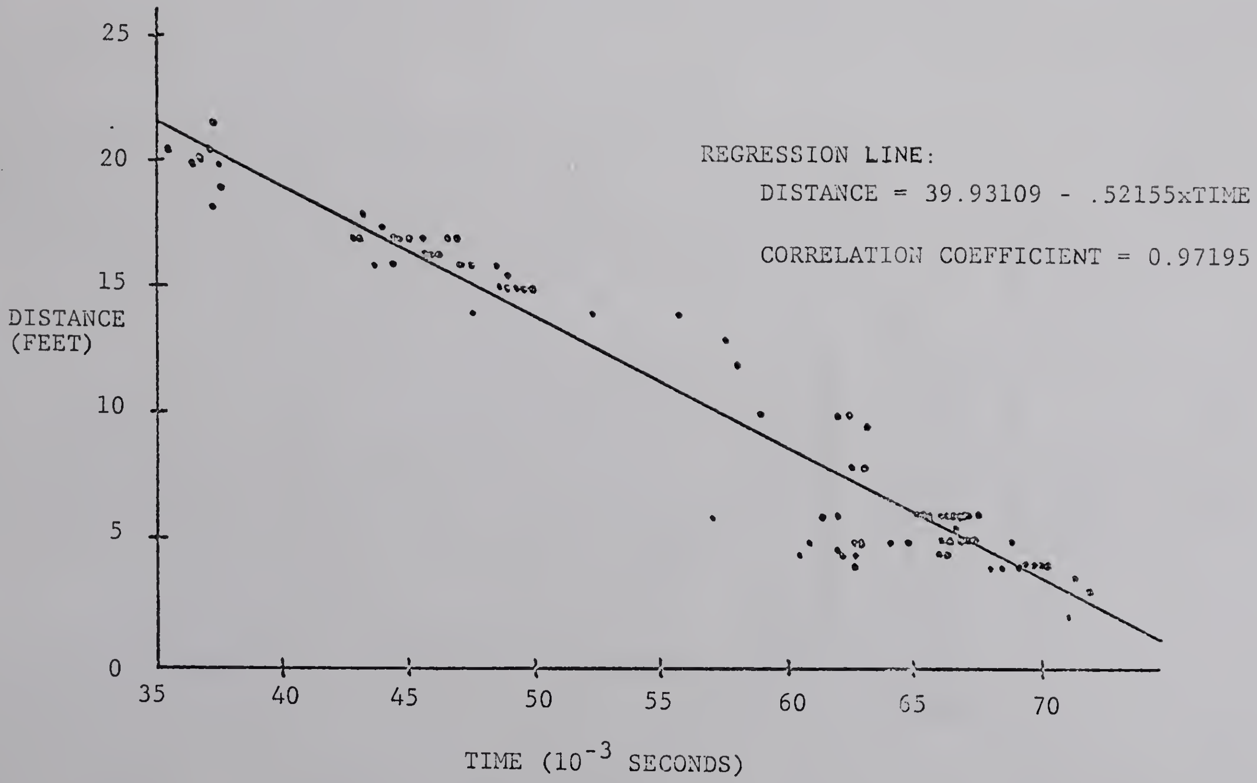


Figure 46. Data for the Calibration of the Sonic Detector Used for the Tampa Green Band System

ed of tabulating the separation of the left side of ramp vehicles from the left side of the freeway shoulder lane, as given by the following expression:

$$SEP_i = OFFSET_k - D - WIDTH + LANE$$

where SEP_i = distance from the left side of ramp vehicle i to the left side of the freeway shoulder lane (feet),

D = sensor to vehicle distance, as above (feet),

$OFFSET_k$ = distance from sonic sensor k to outside freeway lane (feet),

$WIDTH$ = assumed ramp vehicle width (6 feet),

$LANE$ = width of outside freeway lane (feet).

This derived distance measurement could then be used directly to determine when a ramp vehicle merge had occurred, as the distance from the center line to the outside freeway lane line was 12 feet, and any time a ramp vehicle displacement of less than 12 feet was recorded, it could be assumed that the vehicle had entered the freeway outside lane, and had been committed to a merging maneuver.

Figure 47 shows representative output from sonic detector activity analysis generated by the TOGAP software.

```
TEST 1     AFTER PROCESSING WITH FULL OUTPUT (NO PUNCH)   TUGM31/1

DISTRIBUTION OF SEPARATION OF LEFT SIDE OF RAMP VEHICLES FROM LEFT BOUNDARY OF FREEWAY SHOULDER LANE...
 DISTANCE                                          SONIC DETECTOR NUMBER
  (FEET)        1          2          3          4          5          6          7          8          9         10         11

------------------------------------------------------------------------------------------------------------------------------
     1          0          0          0          0          0          0          0          0          0          0          0
     2          0          0          0          0          0          0          0          0          0          0          0
     3          0          0          0          0          0          0          0          0          0          0          0
     4          0          0          0          0          0          0          0          0          0          0          0
     5          0          0          0          0          0          0          0          0          0          0          0
     6          0          0          0          0          0          0          0          0          0          0          0
     7          0          0          0          0          0          0          0          0          0          0          0
     8          0          0          0          0        128         11          9         43          7          2          1
     9          0          0          1          4         69          3          4         18          4          2          0
    10          0          0          1          3         73          6          7          4          1          5          0
    11          1          3          3          2         64          4          5          3          1          2          0
    12          0          0          3          6         60          5         10          3          2          0          0
------------------------------------------------------------------------------------------------------------------------------
    13          0          2          5          9        122          7          0          2          2          1          0
    14          0          3         11          8         47          4          4          4          2          0          0
    15          0          8         33          6        131          4          5          2          1          0          0
    16          1         14         31         10        217          5         28          0          0          0
    17          0         14         47          3         13          4         14         71          2          0
    18          0          6         13          2          1          0          8        170          1          0
    19          0          3          2          0          0          0          0         66          0          0
    20          0          1          0          0          0          0          0          0          0          0
    21          0          0          1          1          0          0          1          0          0          0
    22          0          0          0          0          0          0          0          0          0
    23          0          0          0          0          0          0          0          0          0
    24          0          0          0          0          2          1          0          0          0
    25          0          0          0          0          1          0          0          0          0
    26          0          0          0          0          0          0          0          0
    27          0          0
    28          0
    29          0
    30          0

COUNT           2         54        151         54        928         54         95        365         23         12          1

MEAN          0.0     16.692     16.400     14.316     13.301     12.741     14.721     16.772     11.696     10.240        0.0

STD           0.0      2.004      1.849      2.689      3.117      3.476      3.478      3.860      3.106      1.257        0.0
```

Figure 47. TOGAP Output from the Sonic Detector Analysis of Lateral Vehicle Displacements in the Merging Maneuver

The distribution of vehicle distances from the freeway reference line is printed, as well as the mean reported vehicle distance and standard deviation for each of the eleven sonic detector stations. This information can then be used to estimate the actual system merge point associated with ramp vehicle behavior under green band system control, as was done manually in the analyses discussed at the end of Chapter 3.

Problems have been experienced with the sonic detectors in the Tampa system relating to the need for using long cables between the transducer heads mounted on the acceleration lane guard rail and the associated detector electronics located in equipment cabinets under the elevated freeway and ramp structures. For example, the pulse count for sonic detector actuations at location S5 (see Figure 47) is consistently higher than that reported at any of the other sonic stations, and this location has the longest cable run of any of the sonic units. Swapping of detector electronics and transducer heads among the stations does not change this condition, and no satisfactory method of tuning the circuitry to correct this problem has been found.

Analysis of Control System Behavior

Recall that the green band system as implemented in Tampa has four modes of operation, which are an initialization mode, stopped-metering, stopped-gap acceptance, and moving mode operation. To evaluate the changes between the various operating modes and the distribution of times spent in these modes, subroutine MODEXX is used in the TOGAP system to monitor mode change activity. Substantive changes were made in the routine in the Woburn Green Band analysis software which performed this function, and the entire MODEXX routine is flow-charted in Figure 48 to illustrate the decision logic required to follow mode state changes in the presence of the potential masking conditions associated with the Tampa system operation. A typical output from the MODEXX routine is shown in Figure 49 which gives the distribution of times spent in each mode of operation, the total time spent in each mode, the average time and standard deviation of the time spent in each mode, and the number of changes to each mode. Information on the total time the system was masked in the stopped-gap acceptance modes and the moving modes of operation is also provided to indicate the relative degree of ramp congestion present during these periods. As with the green band/ramp vehicle interaction outputs, Figure 49 represents an application of the TOGAP program to a data tape which did not contain system masking information; thus the values shown for the percentage of time masked in both the stopped-gap and moving modes of operation represent incorrect values and should be considered as the total time spent in

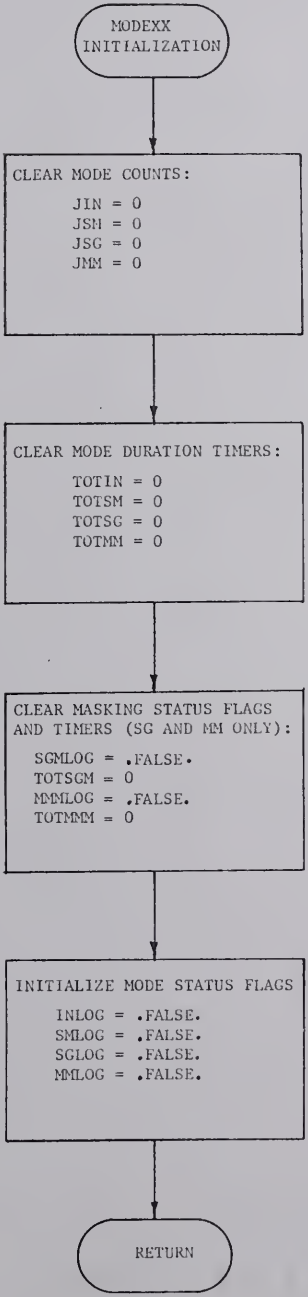


Figure 48. Flow Chart of Routine MODEXX

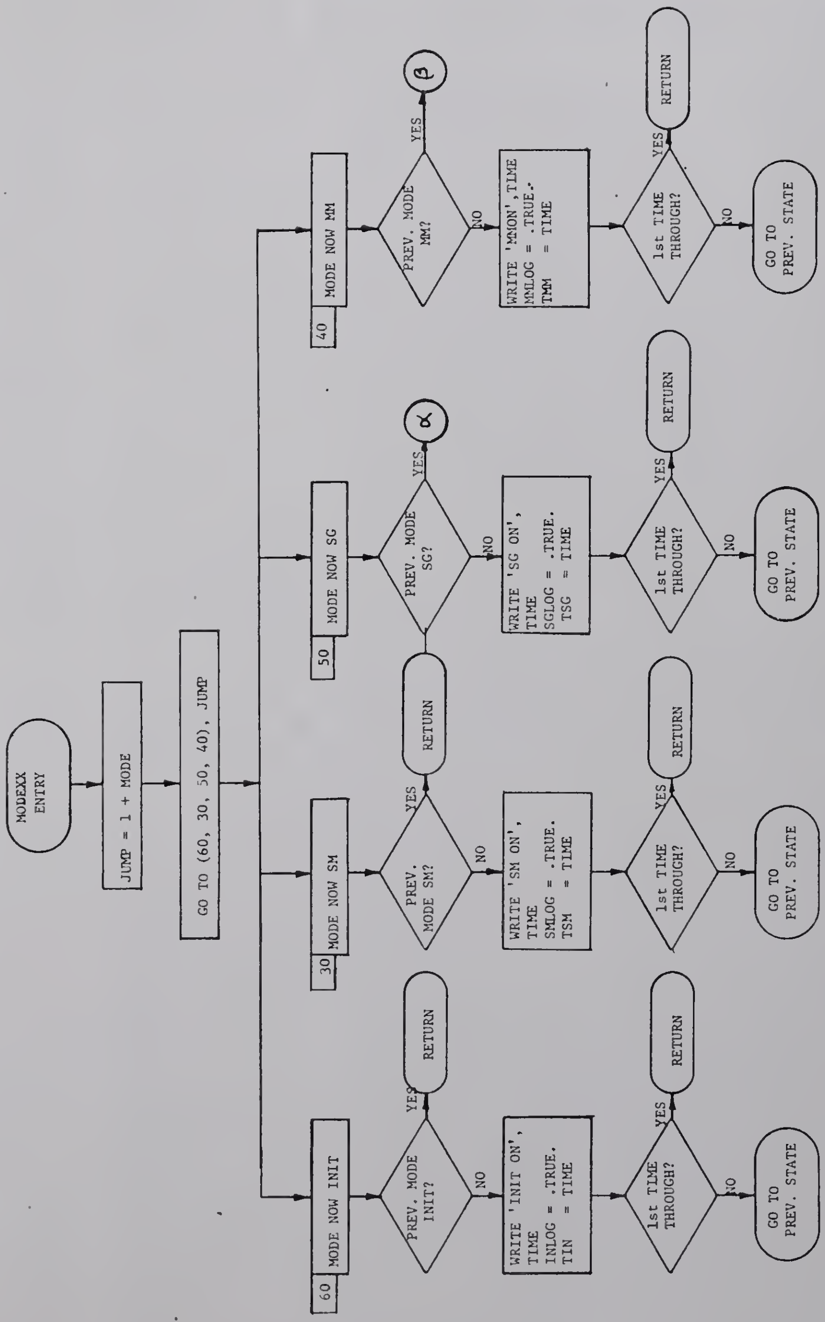


Figure 48--Continued

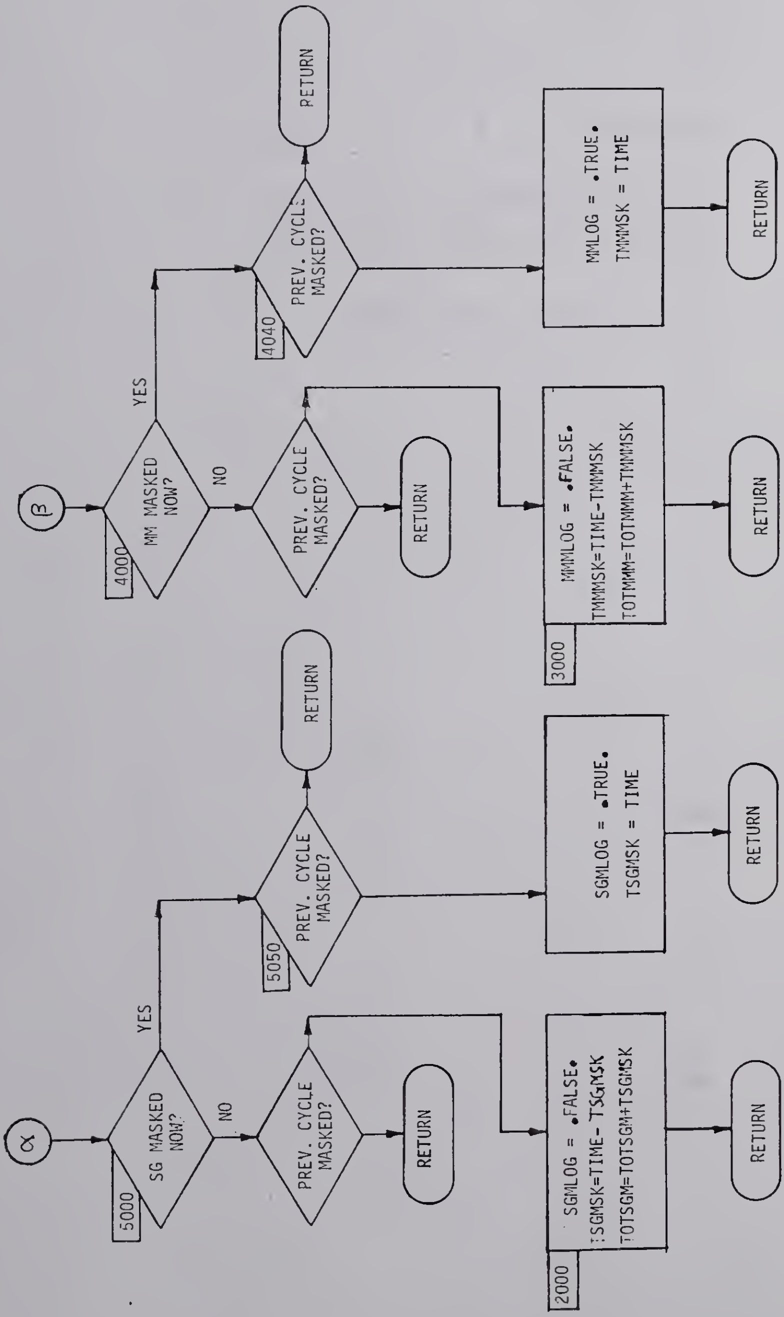


Figure 48--Continued

PREVIOUS STATE LOGIC FOR MODEXX ROUTINE

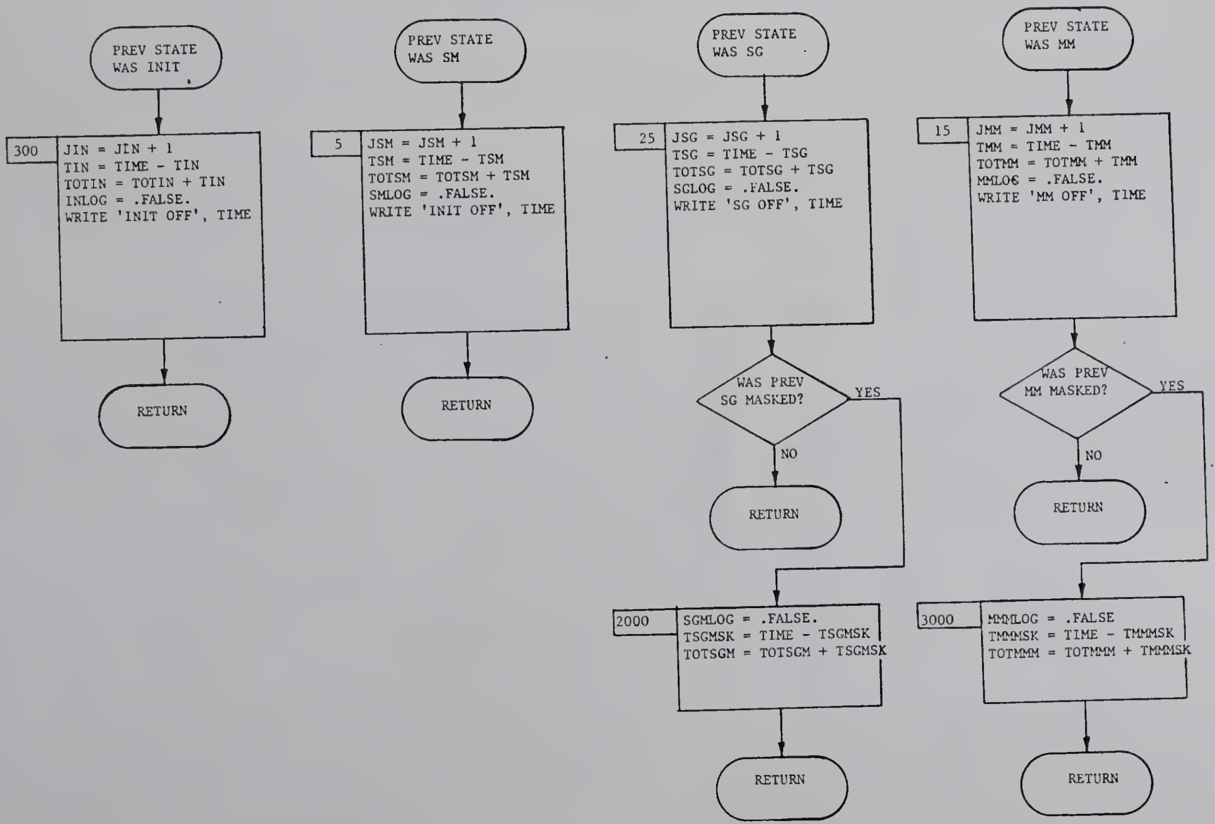


Figure 48-- Continued

```
TAPE = TOGM31, AUG 9, 1974,  7:15 AM  (1 WEEK AFTER OPENING)

DISTRIBUTION OF SYSTEM MODAL BEHAVIOR

                     CLASS              NUMBER IN CLASS FOR EACH MODE
                     LIMIT          INIT             SM              SG              MM

                      2 MIN          0               0               0               0
                      4 MIN          0               0               0               1
                      6 MIN          0               0               0               0
                      8 MIN          0               0               0               0
                     10 MIN          0               0               0               0
                     12 MIN          0               0               0               0
                     14 MIN          0               0               0               0
                     16 MIN          0               0               0               0
                     18 MIN          0               0               0               0
                     20 MIN          0               0               0               0
                     22 MIN          0               0               0               0
                     24 MIN          0               0               0               0
                     26 MIN          0               0               0               0
                     28 MIN          0               0               0               0
                     30 MIN          0               0               0               0
                     32 MIN          0               0               0               0
                     34 MIN          0               0               0               0
                     36 MIN          0               0               0               0
                     38 MIN          0               0               0               0
                     40 MIN          0               0               0               0
                     42 MIN          0               0               0               0
                     44 MIN          0               0               0               0
                     46 MIN          0               0               0               0
                     48 MIN          0               0               0               0
                     50 MIN          0               0               0               0
                     52 MIN          0               0               0               0
                     54 MIN          0               0               0               0
                     56 MIN          0               0               0               0
                     58 MIN          0               0               0               0
                     60 MIN          0               0               0               0
                    >60MIN           0               0               0               0

TOTAL TIME
IN MODE                         0.0             0.0             0.0          300.016

AVERAGE TIME
IN MODE                         0.0             0.0             0.0             0.0

STD OF TIME
IN MODE                         0.0             0.0             0.0             0.0

NUMBER OF CHANGES
TO THIS MODE                     0               0               0               1

PERCENT OF TOTAL
TIME SPENT IN MODE                0.0             0.0             0.0           100.0

ANALYSIS OF SYSTEM GREEN BAND MASKING BY MODES...
SG. MASKED FOR       0.0    SECONDS,OR  0.0    PERCENT OF TOTAL TIME
MM. MASKED FOR     299.504 SECONDS,OR 99.808 PERCENT OF TOTAL TIME
```

Figure 49. TOGAP Outputs for Green Band Control System Mode and Masking Activity

each of these modes. The on-line data logging programs were modified to record system masking information on tape in late September of 1974, and runs made after this date have this information represented correctly.

Information on the reliability of sensors used for the control system is available to a limited extent from an examination of vehicle counts reported for each of the sensors in the freeway and ramp sequences. For example, if a given sensor is reporting a value noticeabley lower than that of the sensors on either side of it, it may be assumed that the sensor was out of adjustment during that particular study run, allowing the data collected for that period to be ignored, avoiding the possible production of invalid performance results.

As indicated earlier in the overall discussion of the TOGAP system operation, provisions are included for punching data on merge vehicle arrival times at sensor locations in the merge area, as well as for punching information on freeway vehicle estimated times of arrival at the merge point. Routines TRACK and FMDSAV, respectively, perform these functions. This approach of punching data on cards for subsequent analysis by other programs was adopted to facilitate the attempt described earlier to reduce the running times associated with the programs in the TOGAP series. An additional benefit of having the merging operations data base available on punch cards was that special purpose analysis programs developed for this activity could be used repeatedly on a given study period's data without the expense and computer time associated with re-reading the system data for the period.

Figure 50 shows representative vehicle trajectories generated by the TOGAP plotting software using punched vehicle data from routines TRACK and FMDSAV. This output was produced on a Gould Model 5100 Electrostatic printer/plotter. Freeway vehicles are projected from F1 downstream, and appear on the graph as straight line segments. Ramp vehicle arrival times at the merge area sensors M1 through M8 are plotted as discrete points, denoted on the graph by small boxes. This output format allows a determination of gap acceptance and rejection behavior for ramp vehicle drivers to be made for each sampling period. Some manual filtering of the derived data is necessary in this process for two basic reasons:

1. The freeway vehicle velocity data obtained at F1 are used to project each freeway vehicle downstream through the merge point. As this represents a distance of 384 feet, some variation in freeway vehicle velocity

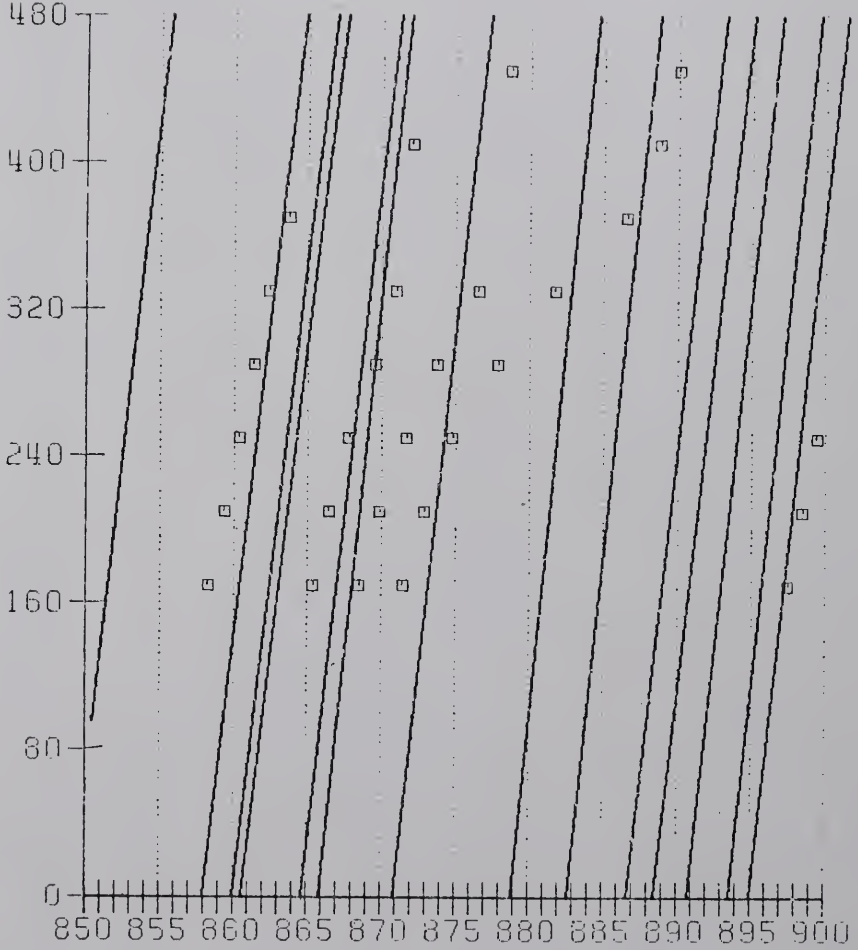


Figure 50. Computer-Generated Plot of Ramp and Freeway Vehicle Trajectories Produced by TOGAP Software

in the actual system is highly probable over this distance, and the use of simple linear projection from F1 can occasionally result in the display of two freeway trajectories which cross at some point in time. This would represent a rear-end collision on the freeway, and as these are extremely rare, the plotted data must be considered in this case to be representative of freeway drivers who have adjusted their respective vehicle speeds to avoid this situation.

2. The merge area presence sensors are 25 feet in length, and under conditions of slow moving ramp traffic, two vehicles may be in a single sensor at the same time, causing a loss of a data point for the trailing ramp vehicle.

In either of the above cases, manual judgment based on consideration of trajectory conditions observed over a time span in front and back of the area in question can be applied to attempt to resolve the ambiguity, or to make the decision to disregard these data in the current analysis.

A new technique for assessing the traffic operational benefits of moving merge control system was coded in the TOGAP software. To implement this technique, subroutine FGPMR1 is called from subroutine TRACK each time a ramp vehicle enters R1, which is the last ramp sensor upstream of the merge area. The freeway vehicle merge ETA table generated by the FMDSAV routine is searched to find a freeway gap corresponding to the expected time of arrival of the ramp vehicle at the merge point. Statistics for this projected gap are accumulated. If the system is operating as designed, and the ramp vehicle drivers are following the green bands on the field display, the distribution of "gaps matched" by the system will in theory evolve from a random or uniform distribution to a distribution which is clustered about the average gap size being used by the green band control program to generate green bands. Figure 51 shows representative output from TOGAP for this type of analysis.

Operational Characteristics of the TOGAP Software

The programs comprising the TOGAP system require approximately 246,000 bytes of core storage for execution on the IBM 370/165 computer. While exact rates will vary with the levels of freeway and ramp vehicle demand in a given study period, one hour of operational system data can be analyzed in approximately four minutes of computer time,

```
TEST 1      AFTER PROCESSING WITH FULL OUTPUT (NO PUNCH)   TOGM31/1


                DISTRIBUTION OF FREEWAY GAPS MATCHED AT R1
NUMBER OF OBSERVATIONS =     48.
MAXIMUM VALUE OBSERVED =    0.228152E 02
MINIMUM VALUE OBSERVED =    0.507275E 01
MEAN VALUE OF DATA =    0.116344E 02
VARIANCE OF DATA =   0.218176E 02
STANDARD DEVIATION OF DATA =    0.467093E 01
HISTOGRAM CELL WIDTH =    0.100000E 01

---------------------------------------------------------------------------------------
CLASS       | NUMBER  | CUM      | CUM     | F R E Q U E N C Y   D I S T R I B U T I O N
UPPER       | IN      | TOTAL    | PER     |  (EACH STAR =        1.0 OBSERVATIONS)
LIMIT       | CLASS   | CASES    | CENT    |
---------------------------------------------------------------------------------------
0.1000E 01|        0|        0|    0.0 |
0.2000E 01|        0|        0|    0.0 |
0.3000E 01|        0|        0|    0.0 |
0.4000E 01|        0|        0|    0.0 |
0.5000E 01|        1|        1|    2.08|*
0.6000E 01|        7|        8|   16.67|*******
0.7000E 01|        5|       13|   27.08|*****
0.8000E 01|        5|       18|   37.50|*****
0.9000E 01|        2|       20|   41.67|**
0.1000E 02|        5|       25|   52.08|*****
0.1100E 02|        5|       30|   62.50|*****
0.1200E 02|        4|       34|   70.83|****
0.1300E 02|        0|       34|   70.83|
0.1400E 02|        2|       36|   75.00|**
0.1500E 02|        1|       37|   77.08|*
0.1600E 02|        3|       40|   83.33|***
0.1700E 02|        1|       41|   85.42|*
0.1800E 02|        3|       44|   91.67|***
0.1900E 02|        1|       45|   93.75|*
0.2000E 02|        1|       46|   95.83|*
0.2100E 02|        1|       47|   97.92|*
0.2200E 02|        1|       48|  100.00|*
REMAINING ENTRIES ARE ALL ZERO...
```

Figure 51. TOGAP Outputs for the Distribution of Freeway Gaps Matched by Ramp Vehicles Detected at Sensor R1

which compares favorably with the estimate of four minutes of CPU time required to process one-half hour of operational data reported by Raytheon for the Woburn Merge Control System analysis software [80, p. B-1].

CHAPTER 5
DESIGN CONSIDERATIONS FOR FUTURE MERGE CONTROL SYSTEMS

Introduction

Design considerations for future merge control systems will be reviewed in this chapter with respect to problems observed to date in the public operation of the Tampa Green Band System. Theoretical improvements to alleviate some of these problems will be presented, and the development and use of a simulation model of the on-line control program to provide a research tool for the analysis of moving-mode system operation will be discussed. A review of essential system functions in future moving merge control systems of the green band type will be used to establish a preliminary hardware design concept for a single-package controller for such systems.

Several areas of observed system performance in the current Tampa Green Band System have been identified as representing potentially undesirable factors in the safe and efficient operation of the moving merge control strategy for freeway entrance ramps. These problem areas fall into two basic categories, the first relating to band generation and stability on the ramp display, and the second relating to the open-loop control philospphy used in the green band system design concept.

As reviewed in Chapter 2, for the Woburn system, and Chapter 3, for the Tampa system, the generation of green bands for display alongside the entrance ramp is done by monitoring detected gaps in the freeway traffic upstream of the ramp, classifying these gaps into acceptable and non-acceptable categories for use by merging vehicles, and then controlling band size and movements on the ramp display using expected travel times to the merge point and safety margin allowances to account for unexpected vehicle behavior. One shortcoming of the current Tampa system that has been noted by a number of observers who have watched the system over extended periods of time during public operation is that the system appears to be too conservative in its band launching decision logic in the moving mode of operation, e.g., bands are frequently not displayed for freeway gaps which appear to be of adequate size for safe merging operations to be accomodated using these gaps. While this condition is certainly to be preferred over that of a situation involving the selection of gaps which are too small for use in band control, it can contribute to a reduction in the controlled merging capacity achievable by the green band system. An analysis of the on-line control program gap evaluation logic was conducted, and the results of this study are discussed in the next section.

Errors in the Computation of the Required Freeway Gap Size in the On-line Control Program

The on-line control computer for the Woburn Green Band System is a fixed point, 16-bit binary machine without hardware multiply/divide capabilities in the basic configuration [90, 91]. This fact apparently necessitated Raytheon's use of numerical approximation techniques to allow the required gap computations outlined in Chapter 2 to be carried out while the on-line system was operating without substantially increasing the running time cycle of the program. For example, the equation representing the time (in seconds) required for a vehicle to accelerate from V_1 to V_2 at some assumed acceleration rate whose (acceleration, velocity) intercepts are $(0, V_0)$ and $(\alpha, 0)$ is

$$F(V_1, V_2) = (V_0/\alpha V_2)[V_2 - V_1 + (V_0 - V_2)\mathrm{LOG}_e \\ ((V_0 - V_2)/(V_0 - V_1))]$$

Values for V_0 and α were taken to be 146.7 feet/second and 5 feet/second^2, respectively, and the equation was approximated by

$$F(V_1, V_2) = \begin{cases} 0.057(V_2 - V_1), & (V_2 - V_1) \leq 17.5 \text{ ft/sec} \\ 0.11(V_2 - V_1) - 0.925, & 17.5 \text{ ft/sec} < (V_2 - V_1) < 41 \text{ ft/sec} \\ 0.16(V_2 - V_1) - 2.85, & 41 \text{ ft/sec} \leq (V_2 - V_1) \leq 128 \text{ ft/sec} \end{cases}$$

To test the accuracy of this approximation, and to identify its possible effects on the operation of the green band system, a computer model of the actual equation for $F2(V_1, V_2)$ and of the approximating equations was developed. The program computes F2 values for a range of given V_1 and V_2 conditions using both the actual formula and the approximation scheme, and prints actual times and estimated times and the corresponding estimation error (in seconds).

The results of this experimentation revealed a bias towards the conservative side (e.g., longer computed times to complete the acceleration maneuver) for every condition tested, as shown in Table 6, which is based on the use of a V1 value of 45 miles/hour, representing the maximum propagation speed of the green band. As the terminal green band speed in the moving mode in the Tampa system is usually at its maximum value of 45 miles/hour, since freeway vehicle speeds have been averaging at 55 miles/hour (the posted limit on the freeway), the approximations for the F2 calculations have the net operating effect of biasing the size of the required gap on the freeway for green band generation to a value some 0.317 seconds higher than it should

Table 6
Illustration of the Numerical Errors in the Equations Used in the Woburn and Tampa Green Band Systems for a Term in the Required Freeway Gap Size Computations

V1 (MILES/HOUR)	V2 (MILES/HOUR)	$F2_{TRUE}$ (SECONDS)	$F2_{EST}$ (SECONDS)	ERROR (SECONDS)
45	46	.00586	.08379	.07793
	47	.02309	.16758	.14449
	48	.05120	.25137	.20017
	49	.08973	.33516	.24543
	50	.13829	.41895	.28066
	51	.19652	.50274	.30622
	52	.26409	.58653	.32244
	53	.34071	.67032	.32961
	54	.42612	.75411	.32799
	55	.52009	.83790	.31781

be. This is a conservative error, as it does provide an additional safety margin in the merging process, but does have the effect of reducing the number of green bands generated over a period of time, thereby reducing the maximum theoretical merging capacity achievable by the system if every ramp vehicle were to wait for a green band.

There are several possible remedies to these computational error discrepancies. The first would be to call for a full-scale evaluation of the original formula when a value is needed through the use of a new subprogram for F2 which performs all the required computations. Given that processing time was in fact a constraint, however, an alternative approach would be to code a table of pre-stored values which could be entered to supply the acceleration time information for various sets of V1 and V2 values. This method would trade-off a greatly reduced computational effort for the accuracy required against a need for extra core storage space in the control program.

As the Tampa Green Band System represents a research-oriented installation, the extra safety margin in the merging operations provided by the errors outlined above was not changed. Future merge control projects at ramps where it is deemed necessary to obtain the maximum achievable merging capacity may need to implement tighter acceptable gap constraints to achieve this goal, and a careful analysis of all elements in the gap evaluation process would be appropriate in such cases. If one was interested in minimizing both computer processing requirements and core memory size in the on-line control program, the required gap logic could be replaced with a simple table of values representing the minimum acceptable gap as a function of the average freeway speed only. The table look-up process in this case would need to be used only when the freeway velocity average had changed by more than some established tolerance.

Another potential problem area with the Tampa system operation (and with that of its Woburn predecessor, as will be discussed later) is the frequent appearance of sudden length or position jumps in the bands on the driver display. This question of band stability, or lack thereof, does not appear to be particularly troublesome to ramp drivers who have responded to the public opinion survey to date, as evidenced by a lack of mention of this situation in the comments section of the questionnaires. To provide an understanding of the band stability problem for possible correction in future systems, however, several studies of system areas concerned with band propagation on the field display were made; these are discussed in the next three sections.

Need for Sensor Calibration in the Determination of Freeway Vehicle Lengths

Accurate real-time information on freeway vehicle length characteristics is needed in a moving merge control system of the green band type for two basic reasons:

1. Freeway vehicle length data are used in the computation of measured gaps in the freeway traffic stream to establish those gaps which will be used for the creation of green bands to guide ramp vehicles.

2. Given that an acceptable gap has been identified, freeway vehicle length data are used in the computations of the band placement on the display element to insure adequate safety margins around the programmed freeway gap.

The two considerations above suggest potential difficulties with any observed length data which differ from nominal values on either end of the measurement error spectrum. For example, length data which are biased towards high vehicle lengths reduce the number of freeway gaps which will be classified as acceptable for the merging traffic at a ramp, thereby reducing the service capacity of the merging control system. Conversely, length measurements which are biased towards small length measurements can result in the use of freeway gaps which are too small for adequate vehicle spacings in the merging process, although the supplied headway allowances for band placements on the driver display will reduce the safety hazards associated with this problem.

This question of vehicle length measurement accuracy can be related to the statistical properties associated with the average value, or mean, of the observed measurement data at a given sensor location. Another area of concern is related to the stability of the length measurements reported as freeway vehicles travel through the sensor stations along the freeway lane upstream of the merge area. In a dynamic merge control system such as the green band concept, the length variations associated with a single vehicle as it travels through the system can cause band jumps back and forth on the display, as well as the more serious problem of entire bands suddenly appearing and disappearing on the display if the measured freeway gap associated with these bands oscillates around the value of the required gap control parameter for the vehicles defining the gap.

Analysis of data produced by the TOGAP data reduction programs revealed some interesting results on average freeway vehicle lengths as reported at the seven sensor stations located upstream of the Ashley Street ramp in Tampa.

Table 7 summarizes this freeway vehicle length data, which were taken in two successive 15-minute periods while the green band system was in public operation on August 9, 1974.

The discrepancy in vehicle counts across the various stations is caused by freeway vehicles moving in and out of the outside lane as they "jockey for position" in the freeway traffic flow. Note the variation in observed mean length values across the sensors in both 15-minute sampling periods. In the Tampa on-line green band system, measurement differences of this magnitude can cause difficulties with band positioning as discussed above. For example, assuming an average freeway vehicle speed of 50 miles/hour (73.5 feet/second), the measured time length of an average vehicle passing from sensor F4 to sensor F3 in the first data set would change from:

$$\text{VEHICLE TIME LENGTH at F4} = \frac{\text{LENGTH}}{\text{VEL}} = \frac{16.974}{73.5} = 0.231 \text{ seconds}$$

to

$$\text{VEHICLE TIME LENGTH at F3} = \frac{\text{LENGTH}}{\text{VEL}} = \frac{23.649}{73.5} = 0.322 \text{ seconds,}$$

a difference of 0.091 seconds. If the current green band speed were 45 miles/hour (66 feet/second), the band defining the gap would "shrink" in size by the product of the band speed by the length discrepancy, or (66)(0.091) = 6.006 feet, assuming the other system parameters were held constant.

Table 7
Study Data and Derived Results for Sensor Length Calibration Model

	SENSOR STATION						
	F7	F6	F5	F4	F3	F2	F1
Case I: August 9, 1974 7:15 - 7:30 A.M.							
Number of Freeway Vehicles in Sample	237	234	239	242	252	255	252
Mean Vehicle Length (W = 6 feet)	18.730	19.585	18.313	16.974	23.649	21.926	22.739
Estimated W	7.229	8.085	6.813	5.473	12.149	10.426	11.239
Case II: August 9. 1974 7:30 - 7:45 A.M.							
Number of Freeway Vehicles in Sample	229	239	242	242	256	257	256
Mean Vehicle Length (W = 6 feet)	19.046	19.462	17.810	16.659	24.339	22.530	23.203
Mean Vehicle Length (W as estimated)	17.817	17.452	16.997	17.186	18.266	18.497	18.041

Since the green band display element is constructed of discrete four-foot lengths of fluorescent bulbs, a change of 6.006 feet would be observable in a displayed band edge, and a perceptive ramp driver following the band would be led to the possibly incorrect conclusion that the freeway gap he is being directed to has changed, causing him to slow down to wait for the band, and thus introducing an unnecessary accident conflict.

The application of a similar analysis on the F5 to F4 sensor transition predicts a positive band "jump" along the display for this situation of +1.188 feet, which is too small by itself to be observed. However, if a leading band edge is on the threshold of requiring another display element to represent it at a point in time, say at 203.9 feet, the incremental band size associated with this length measurement error would put this leading edge at 205.088 feet, requiring 51 bulbs to display the band instead of 50, which would be a noticeable effect. A similar argument can be used to demonstrate the possibility of a two-bulb error (8 feet) in the case of the 6.006-foot band edge placement error treated earlier.

The explanation for the discrepancies in the vehicle length measurements across the sensor stations is related to the electronic properties of the individual detector units associated with each loop. Sarasota Mark 15 series detectors were used for freeway vehicle detection based on their observed performance in accurately reporting vehicle arrival times at the leading edge of loops in a series of controlled tests [93]. The speed detection process for the Tampa Green Band System uses two loops at each freeway station, spaced a known distance apart. Then, as a vehicle passes over the two loops, its velocity may be estimated by dividing the loop separation by the vehicle travel time between the loops. The critical factor in this speed determination technique is that both detectors (e.g., one at each loop) report the presence of the vehicle at the same relative position with respect to each of the loops to give accurate travel time measurements over the known loop separation distance. This requirement leads to the need for using loop detectors which are paired, or close to identical in their sensitivity, or rise-time characteristics, with respect to vehicle presence at the leading edge of the associated loops. Rise-time is simply the time required to generate a detector output signal given that a vehicle has disturbed the magnetic flux field of the loop beyond a fixed threshold level.

The detectors used in the Tampa freeway stations were tested for their adequacy in the useage described above, and were found to give satisfactory results for the speed determination application. However, since the detector circuitry was designed specifically for accurate response to leading edge vehicle presence, as indicated, inaccuracies were noted in the times reported by the detectors for vehicle departures from the loops. In particular, each of the pairs of detectors in the seven freeway stations have electrical cut-off thresholds in practice located at distances ahead of or behind the actual loop widths of six feet as installed in the road surface. This has the effect of biasing reported vehicle lengths away from the actual length values. To estimate the magnitude of this error for each sensor pair, and to determine if a calibration technique could be used to correct the errors, the analysis described in the following section was performed.

Derivation of a Model for Estimating Operational Lengths of Freeway Sensors

Recall the scheme used for identifying sensor time events for the double-loop freeway sensors for vehicle i passing through the sensor, and let $T3_i$ and $T4_i$ be the times of vehicle arrival and departure at the first loop in the sensor, and $T1_i$ and $T2_i$ be the times of vehicle arrival and departure at the second loop in the sensor, respectively.

Then, $TT_i = (T1_i - T3_i)$ = Travel time in the sensor of vehicle i from leading edge of first loop to leading edge of second loop

$TOCC_i = (T2_i - T1_i)$ = Occupancy time of vehicle i in second loop of the sensor.

G = Distance from leading edge of the first loop in the sensor to the leading edge of the second loop,

W = Assumed electrical length of second loop (feet).

Then, the velocity of vehicle i in the sensor may be estimated by:

$$VEL_i = \frac{DISTANCE}{TRAVEL\ TIME} = \frac{G}{(T1_i - T3_i)} = \frac{G}{TT_i},$$

and the length of vehicle i may be estimated by

$$LENGTH_i = (T2_i - T1_i) - \frac{W}{VEL_i}, \text{ in seconds}$$

or

$$LENGTH_i = (T2_i - T1_i)(VEL_i) - W$$

$$= (TOCC_i)(VEL_i) - W, \text{ in feet.}$$

Now, consider the computation of the mean length of a series of N vehicles passing over a given sensor station:

$$LENGTH_{avg} = \frac{\sum_{i=1}^{N} [LENGTH_i]}{N}$$

Substituting the expression derived earlier for (LENGTH_i) in the above equation gives:

$$\text{LENGTH}_{avg} = \frac{\sum_{i=1}^{N} [(\text{TOCC}_i)(\text{VEL}_i) - W]}{N}$$

Then, substituting the expression for (VEL_i) derived earlier, it is possible to write:

$$\text{LENGTH}_{avg} = \frac{\sum_{i=1}^{N} \left[\frac{(\text{TOCC}_i)G}{(\text{TT}_i)} - W\right]}{N}$$

Removing the constant G from the expression and expanding yields:

$$\text{LENGTH}_{avg} = \frac{\left[G\sum_{i=1}^{N} \left(\frac{\text{TOCC}_i}{\text{TT}_i}\right) - \sum_{i=1}^{N} W\right]}{N}$$

And finally, dividing the expression by the denominator gives:

$$\text{LENGTH}_{avg} = \frac{G}{N} \sum_{i=1}^{N} \left(\frac{\text{TOCC}_i}{\text{TT}_i}\right) - W$$

Thus, the average length is a function of G, N, $\Sigma\frac{\text{TOCC}_i}{\text{TT}_i}$, and W, as expected, but the expression can be rearranged to allow the computation of W in terms of the other variables, as:

$$W = \frac{G}{N}\left[\sum_{i=1}^{N} \left(\frac{\text{TOCC}_i}{\text{TT}_i}\right)\right] - \text{LENGTH}_{avg}$$

Thus, by assuming an average vehicle length, it is possible to compute an estimated operational length for a given freeway sensor pair, since G is known by measurement (20 feet in the Tampa system) and N and $\sum_{i=1}^{N}\left(\frac{TOCC_i}{TT_i}\right)$ can be obtained from data generated by the on-line system. This theory makes it possible to use a set of individual W values for each sensor in the control program's Highway Vehicle Processing routine which will cause the reported length averages over a set of vehicles at the sensor stations to more closely agree in magnitude, forcing a closer agreement in vehicle length tracking across the sensor set.

To test the validity of the above approach, a computer run was made, using the first 15-minute period's data to estimate sensor width values for the next period. An average freeway vehicle length of 17.5 feet was used at the suggestion of Mr. Gary C. Price, Florida Department of Transportation [personal communication], to provide the desired goal. Average length values for the seven freeway stations are shown with and without the use of these estimated W values in Table 7. The program used data on individual freeway vehicle sensor event times to compute vehicle lengths, which were then averaged to generate the data rather than using the period average length expression derived above. These results have the expected consistent behavior, and would provide an on-line control system with a reduced band jump or shrink potential in normal operation.

It is interesting to note that this algorithm for sensor width adjustment could easily be carried out on-line by a merging control system as it controls the ramp displays. Software routines could be coded to maintain continuous running totals of N and $\Sigma\left(\frac{TOCC}{TT}\right)_i$ from each freeway sensor input. Then, at periodic update intervals, perhaps on the order of several minutes apart, the system could be instructed to compute a new vector $\underline{W}$, representing an adaptive estimate of the electrical length behavior of the freeway sensors for the next period of operation. Since operational experience with the Tampa system has shown that freeway double-loop detectors need frequent adjustment and tuning to keep them operational, the use of an on-line sensor length measurement calibration algorithm such as that discussed above could minimize the disruptive effects of such maintenance operations on the behavior of the merge control system displays.

Development of a Simulation Model for the On-line Green Band System Control Program

As indicated earlier in this chapter, the green bands displayed on the ramp display associated with the Tampa Green Band System frequently exhibit stability problems which have the potential for reducing the degree of ramp driver confidence in the operation of the system. To establish a tool for studying this problem, a simulation model for the on-line control system was developed. The use of simulation techniques was considered to be the best approach for analyzing this problem for the following reasons:

1. Experiments with the on-line system in the field during normal traffic conditions would have necessitated closing the ramp to avoid the display of possibly erratic bands to public traffic. As the ramp volume is moderate to heavy during the day, particularly during peak periods, the closure of the ramp would have caused diversion of traffic in the downtown Tampa central business district, and this was deemed unacceptable. Experimentation with changes in the on-line system using the situation display board to monitor system outputs was a possibility, but would have required photographic data recording of the system operation to slow the system output activity down enough to permit meaningful comparisons to be made (also a requirement associated with the use of the ramp display for experimentation).

2. The use of fixed data inputs such as those that would be required to operate a simulation model would allow controlled experimentation with system parameter or logic changes for exactly the same set of field inputs in each case, allowing an accurate comparison of behavior of the system under these differing conditions. Also, establishing exact reproduceability of field sensor data inputs to the on-line control program to establish the effects of changes in the program or in the parameters associated with the program would have been extremely difficult. It was theoretically possible to write a data processing routine which would read data tapes prepared earlier by the system and to use the resulting data to simulate field sensor inputs, but this approach would have necessitated the creation of special purpose assembly language software to handle this task, and other considerations discussed below made the use of the on-line system relatively unattractive.

3. The green band control program is designed to operate on-line in real time. Figure 52 illustrates the frequencies at which the major rou-

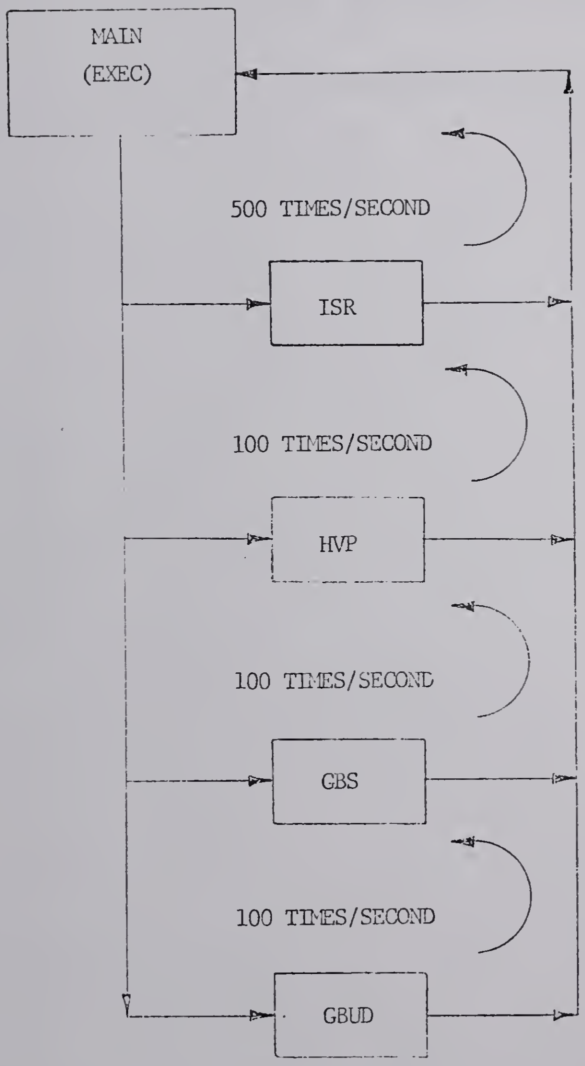


Figure 52. Subroutine Calling Rates in the On-Line Control Program

tines in the on-line control program are called. Note that the input service routine (ISR) is called 500 times per second, and the other routines including the highway vehicle processor (HVP), the green band status program (GBS), and the green band update routine (GBUD) are called at the rate of 100 times per second. These relatively high program activity rates would have necessitated some means of recording the values of the variables associated with these operating routines for subsequent off-line analysis at a rate fast enough not to interfere with the operations of these routines. Thus, again simulation was indicated, as it allows the operations of the process being represented to be run at a rate which allows examination of the appropriate variable values as the simulation progresses without interfering with the normal flow of the operations of the process being simulated.

4. Finally, experimentation with program parameter values is relatively easy in the on-line green band system, as the operator change and inspect routine (OCIS) allows a capability for such changes to be made through the teletype console

while the system is running. However, changes to the program structure, including such minor things as the addition of two or three lines of code in the middle of a routine, require the use of the assembler program for the Raytheon 704 computer to prepare a new program for execution. This necessitates the use of the paper tape editing capabilities of this system to implement the program changes, and then requires the input of this new paper tape to the assembler for preparation of an object tape containing the machine language instructions associated with the program. As the assembler requires two passes with the source language tape to prepare an object tape and produce a corresponding output listing, this process is extremely time-consuming and the use of the on-line system for software experimentation involving frequent program changes would have limited the amount of experimentation that could be conducted in the time available for the project.

It is axiomatic that a simulation model is only as good as its data inputs, and thus considerable attention was paid to the question of providing accurate data inputs to the simulation program which accurately represented those conditions fed to the on-line program by the input service routine (ISR) of the green band control program. As mentioned earlier, the TOGAP program for off-line analysis of on-line data tapes generated by the control system provided an ideal means of obtaining the necessary data, and modifications were implemented in the TOGAP system to provide punched output of freeway vehicle characteristics at each upstream sensor station corresponding to the information available inside the on-line control program. These inputs included for each freeway vehicle, the estimated time of arrival at the merge point, the time of crossing at the leading edge of the second loop of the current sensor, the velocity at the sensor in feet per second, and the length of the vehicle in seconds. TOGAP computes vehicle length measurements in units of feet, but these values can easily by converted to vehicle length in seconds by simply dividing the length in feet by the observed vehicle velocity.

Figure 53 shows the operating environment for the green band control simulator, and illustrates the inputs to the system, the logic elements associated with the simulation, and the outputs obtained from the simulation. As band activity in the moving mode was the primary concern, only the moving mode of system operation was simulated. Figure 54 shows the subroutine structure for the control program

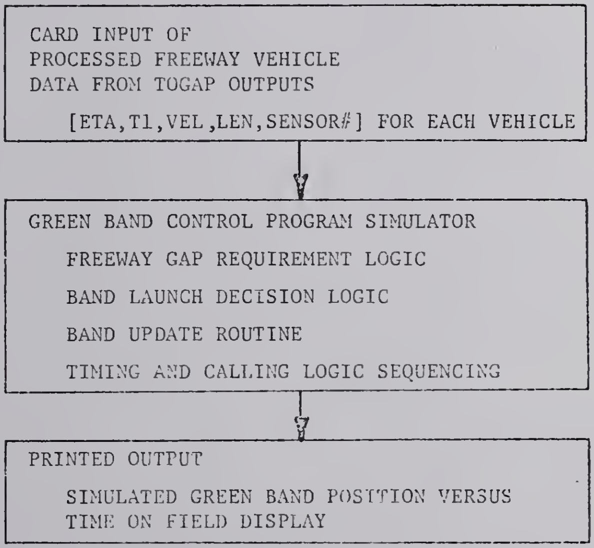

CARD INPUT OF
PROCESSED FREEWAY VEHICLE
DATA FROM TOGAP OUTPUTS
[ETA,T1,VEL,LEN,SENSOR#] FOR EACH VEHICLE
GREEN BAND CONTROL PROGRAM SIMULATOR
FREEWAY GAP REQUIREMENT LOGIC
BAND LAUNCH DECISION LOGIC
BAND UPDATE ROUTINE
TIMING AND CALLING LOGIC SEQUENCING
PRINTED OUTPUT
SIMULATED GREEN BAND POSITION VERSUS
TIME ON FIELD DISPLAY

Figure 53. Operating Environment for the Green Band Control Program Simulator Illustrating Inputs, Logic Elements, and Outputs

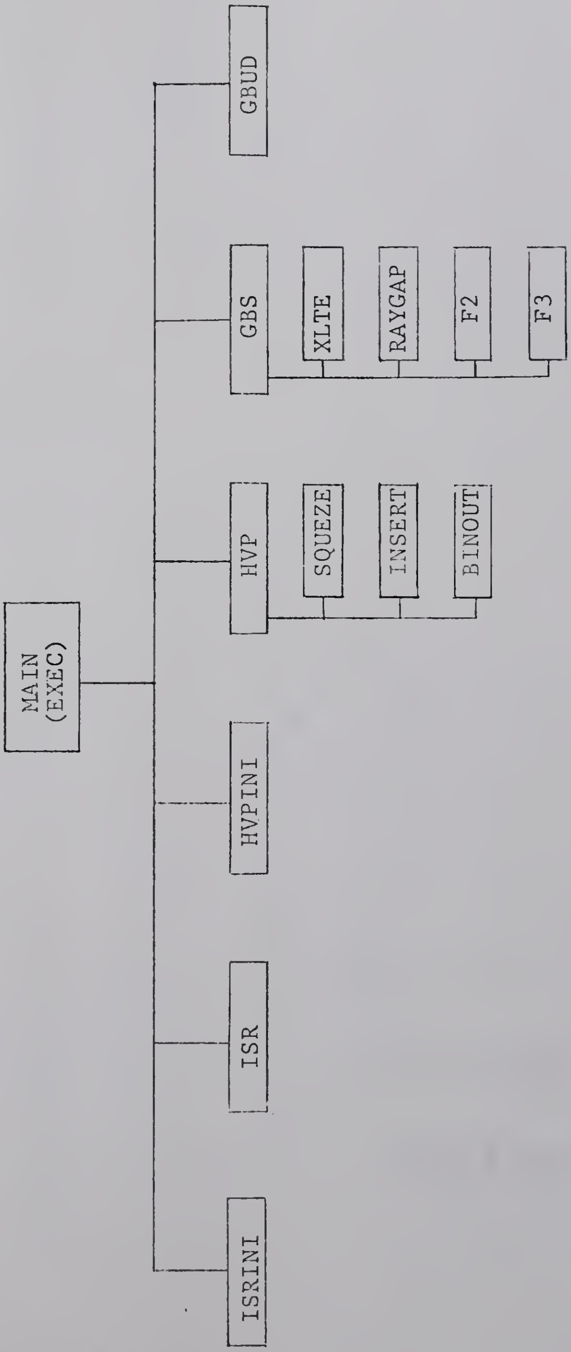


Figure 54. Subroutine Structure for Green Band Control Program Simulator

simulator. The programs were written in the FORTRAN IV programming language, and a complete listing appears in Appendix B. This listing is for the simulator version representing the current Tampa system.

The actions of the executive routine (EXEC) in the control program are simulated by the MAIN routine. When the simulation is run, the first action of MAIN is to call subroutines ISRINI and HVINI to initialize data arrays used by the simulated input service routine (ISR) and highway vehicle processor (HVP) routines of the on-line control program. When these routines have been initialized, the MAIN routine simply calls the other routines of the simulation at simulated rates corresponding to those used in the on-line control system. The only other responsibility of this routine is to update a simulated real-time clock for the system to provide timing information.

Figure 55 illustrates the data storage scheme used to hold the input data from the TOGAP system outputs of actual freeway conditions. The data are stored in a three-dimensional array which can be considered as having 7 rows, 100 columns, and 5 planes for data storage, representing respectively the 7 freeway sensor stations, storage capabilities for up to 100 vehicle observations at each station, and 5 types of data for each freeway vehicle including the ETA at merge point, the time of second loop leading edge crossing

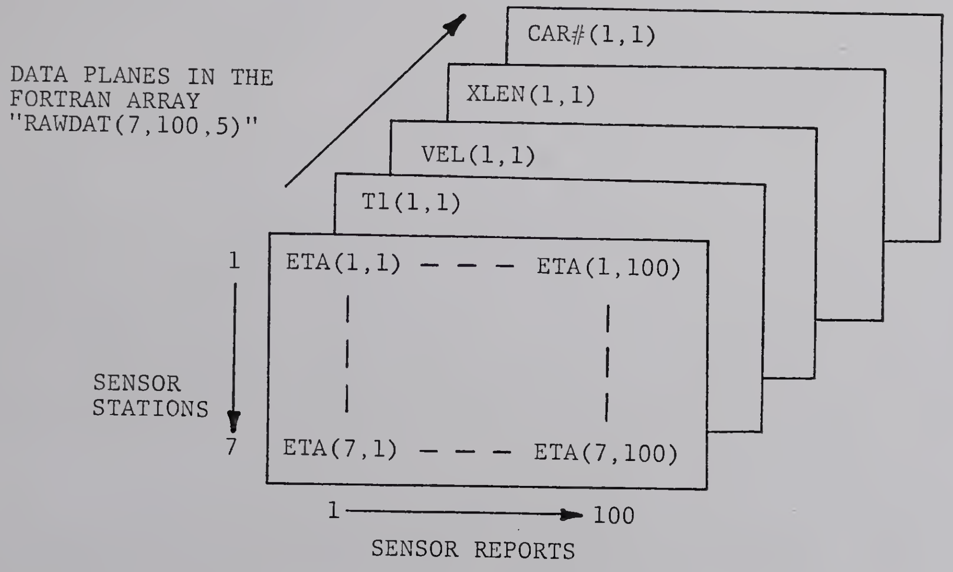
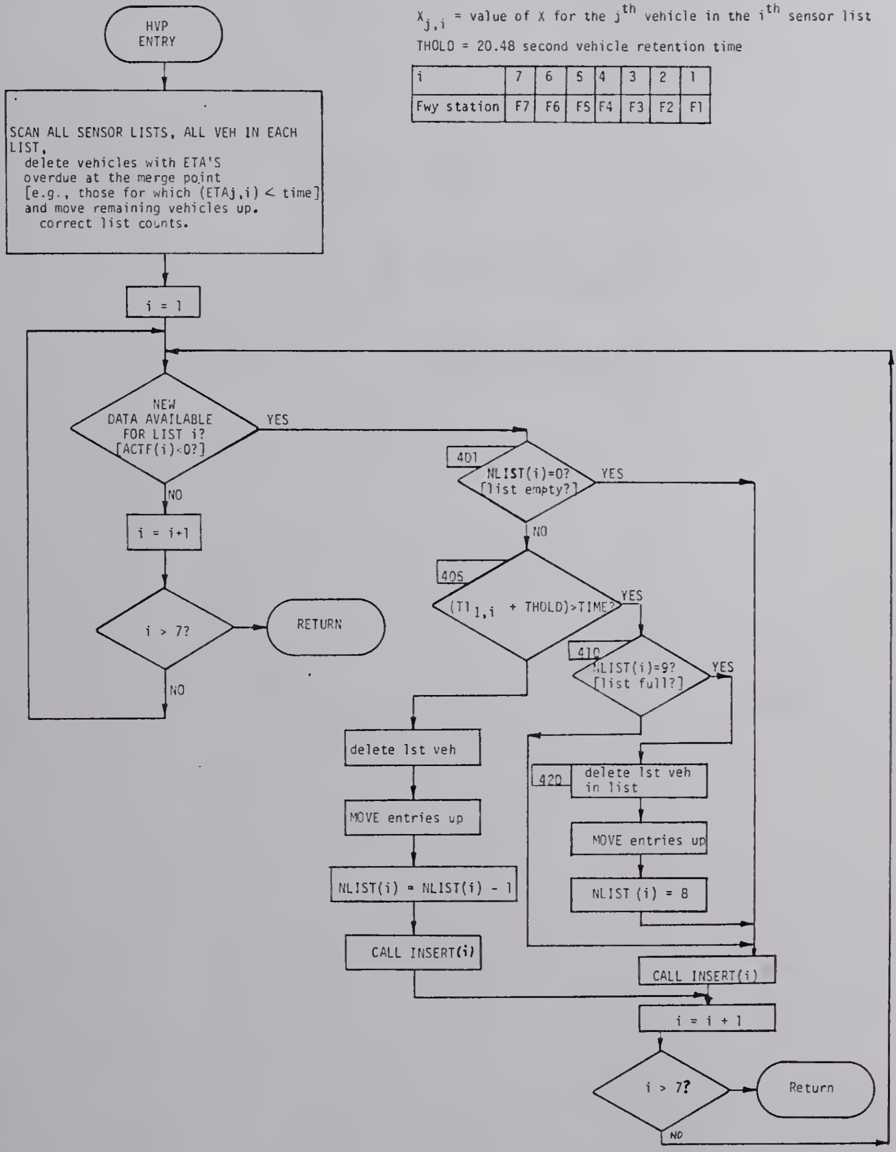


Figure 55. Scheme Used for TOGAP Data Storage in Green Band Simulation Routine

at the velocity sensor station, the vehicle velocity, the vehicle length, and finally the car number obtained by vehicle tracking in the TOGAP system. It should be noted that the on-line control system does not do vehicle tracking, and therefore does not associate vehicle numbers with the various sensor reports that it processes, but these data were included in the simulation of the control program to facilitate the identification of individual vehicles in the various data tables associated with the operations of the system.

To accurately represent the timing of data flows from the field sensors in the simulation of the on-line control program, two single-dimension arrays each of length 7 were used to represent respectively the time at which the next event for each of the seven sensors will occur in the future, and the current array subscript of the vehicle which will be next in a given sensor list. The simulation does not look ahead in time, rather, it uses the information stored on the time of the next vehicle arrival at each of the sensor stations to inhibit sensor activity on each channel until the current clock time is equal to or greater than a projected vehicle arrival time. When this condition is detected, a flag is set in the simulation indicating to the simulated highway vehicle processor routine that new data are available. This is the same technique used in the on-line control system to report the completion of vehicle timing data at a freeway sensor by the input service routine and a subsequent need for processing by the highway vehicle processor routine in the on-line system.

Figure 56 shows the simulation logic used to model the actions of the highway vehicle processing program in the on-line control program. The on-line program and the corresponding simulation model both maintain lists of freeway vehicle data for each sensor station. In the on-line system, 4 pieces of data for up to 9 vehicles are accommodated for each of the 7 freeway sensor stations as discussed earlier in Chapter 2, and the total freeway vehicle data base is maintained in a single data table of 252 words. To facilitate array manipulation in the simulation program, however, separate data arrays are maintained for each of the sensor stations containing enough storage to represent 9 vehicles for each of the stations as in the on-line system. The current number of vehicles in each sensor list is stored in a single dimension array, NLIST(7). As the sensor data from the freeway vehicle actuations have already been processed by the TOGAP system, and are available in prestored data arrays, the computational activity normally performed by the highway vehicle processing program on-line to convert sensor actuation times to vehicle descriptors is not required in the simulation, and the primary activity of the simulated highway vehicle processing program is to schedule the updates of the



$X_{j,i}$ = value of X for the j^{th} vehicle in the i^{th} sensor list

THOLD = 20.48 second vehicle retention time

i	7	6	5	4	3	2	1
Fwy station	F7	F6	F5	F4	F3	F2	F1

Figure 56. Flow Chart of HVP Logic Used in Control Program Simulator

various sensor lists in a manner equivalent to that done by the on-line program. Examination of Figure 56 reveals the basic processes involved in this updating process.

On each entry to the highway vehicle processor, done at the simulated rate of 100 calls per second, all vehicles in all of the current sensor lists are checked against the current time to see if they are overdue at the merge point. This testing is done by comparing the estimated time of arrival for each vehicle at the merge point with the current clock value, and only those vehicles for which the estimated time of arrival is greater than the current clock time are maintained in the lists. The vehicles which are overdue at the merge point are deleted from the lists, and the list counters adjusted to reflect the current number of entries in each list. When this ETA scanning is completed, the highway vehicle processor scans through each of the sensor lists beginning at F1 and working upstream to the simulated list fo F7. For each list, the sensor activity flag set by the simulated input service routine is checked to see if new data are available. If no such data are available, the scan continues at the next upstream list. If, however, new data are available, the list contents counter is checked to see if the list is currently empty. If it is, subroutine INSERT is called to place the new sensor data in the list and to adjust the list counter. If the list is not currently empty, the first vehicle in the list is checked to see if it is overdue at the next downstream sensor. This test is done by comparing the sum of the reported vehicle detection time (T1) plus a vehicle maximum retention time, THOLD, with the current clock time. If this sum is greater than the current clock time the vehicle is considered to be overdue at the next downstream sensor and is removed from the list. If the vehicle is not found to be overtime at the next downstream sensor, the list is checked to see if it is full, and if so, the top entry is deleted, all list elements are moved up one position, and the new data are inserted at the bottom of the list. If the current list is not full, the new data are inserted at the list at the next available position and the counter is adjusted to reflect the number of vehicles currently stored in the list.

Subroutine INSERT performs the functions of placing newly available freeway vehicle data in the respective sensor lists. As indicated by its flow chart, depicted in Figure 57, INSERT also serves to implement the functions performed in the highway vehicle processor in the on-line control system of providing a minimum vehicle ETA separation in the data lists. This is accomplished by checking the estimated time of arrival of the newest vehicle in the list against the estimated time of arrival at the merge point of the vehicle immediately above it in the list, representing the

NOTE: i = vehicle list #, i = 1, ···, 7
HMIN = minimum highway vehicle spacing (0.8 seconds)
$NLIST_i$ = current # of vehicles in sensor list i

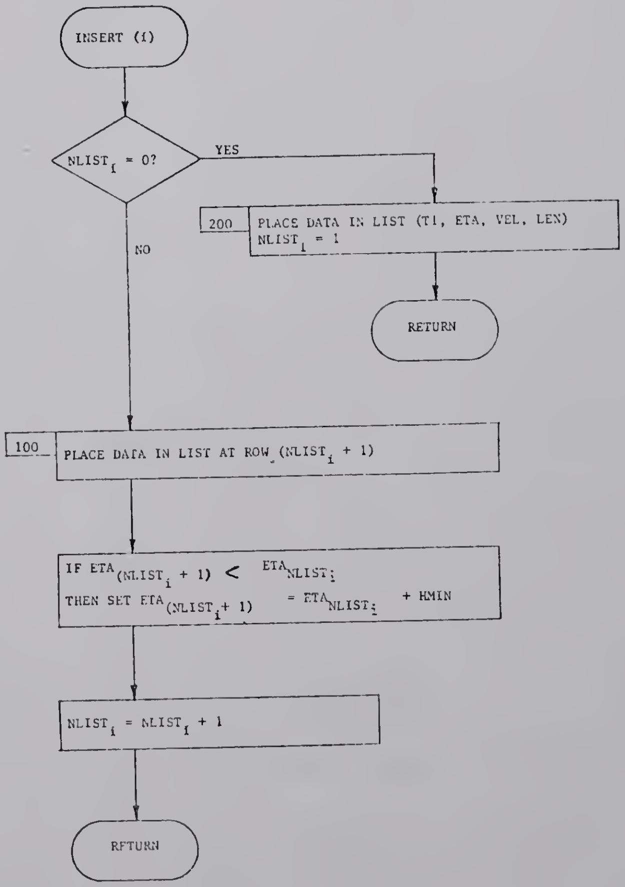

INSERT (i)
NLIST_i = 0?
YES
NO
200
PLACE DATA IN LIST (TI, ETA, VEL, LEN)
NLIST_i = 1
RETURN
100
PLACE DATA IN LIST AT ROW (NLIST_i + 1)
IF ETA_(NLIST_i + 1) < ETA_NLIST_i
THEN SET ETA_(NLIST_i + 1) = ETA_NLIST_i + HMIN
NLIST_i = NLIST_i + 1
RETURN

Figure 57. Flow Chart of Subroutine INSERT

next earlier vehicle currently stored in the list. If this ETA value is less than the previous ETA value, the assumption is made that the new vehicle will slow down to avoid overtaking the previous vehicle, and an ETA value is stored for this new vehicle which represents the old ETA value plus a minimum time spacing, HMIN, which is currently implemented at a value of 0.8 seconds in the on-line control system. After the new vehicle data are placed in the current sensor list, the list counter is adjusted to reflect the availability of new data and the subroutine returns to the simulated highway vehicle processor.

Subroutine SQUEEZE performs the functions of compressing vehicle data list entries at each sensor station when a need for such activity is determined by HVP. This routine essentially performs the same function as that done in the on-line control program when data must be moved in the master freeway vehicle data table.

Green band launch decisions and computations for the placement of green bands on the driver display are performed by the simulated green band status (GBS) routine, whose flow chart is represented in Figure 58. Again, to facilitate the FORTRAN array manipulations required by the simulation, the individual highway vehicle processor sensor lists are copied sequentially into a single array repre-

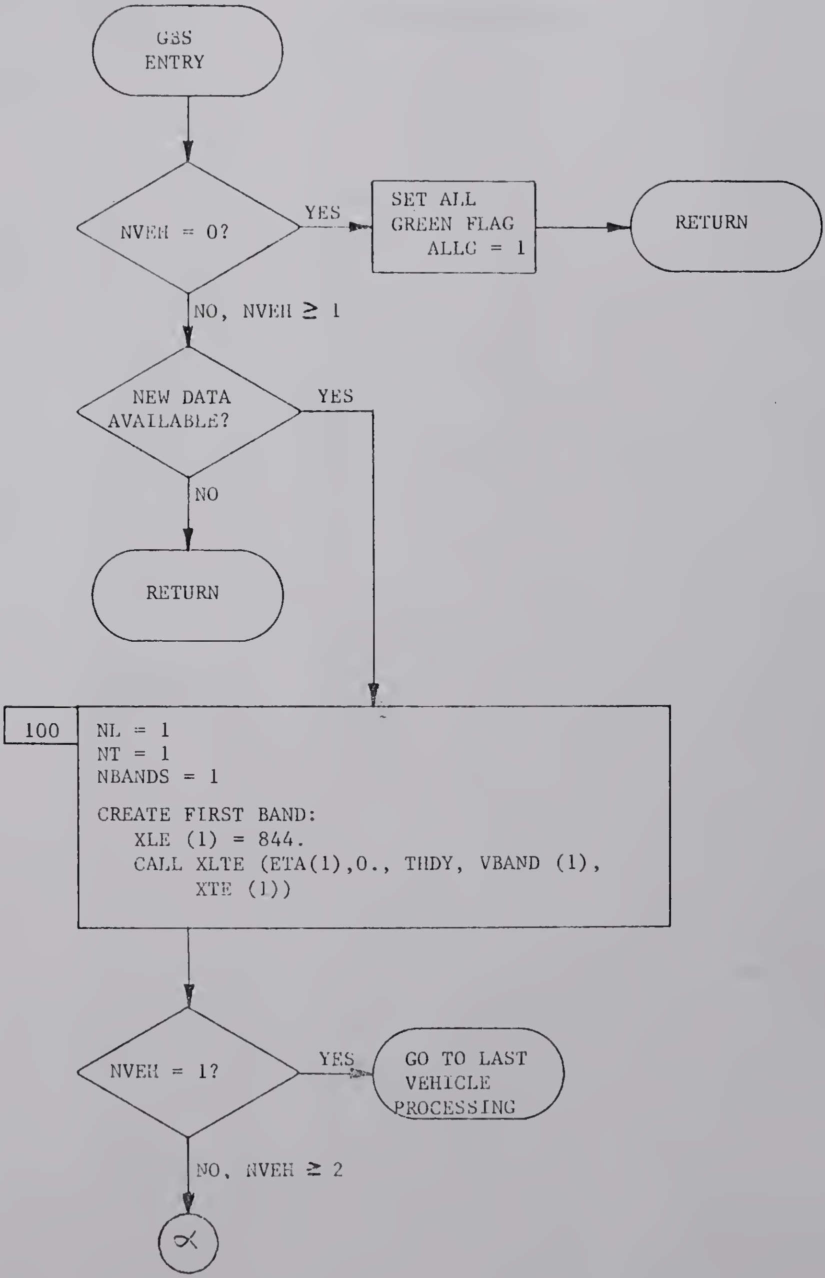


Figure 58. Flow Chart of Green Band Status Routine

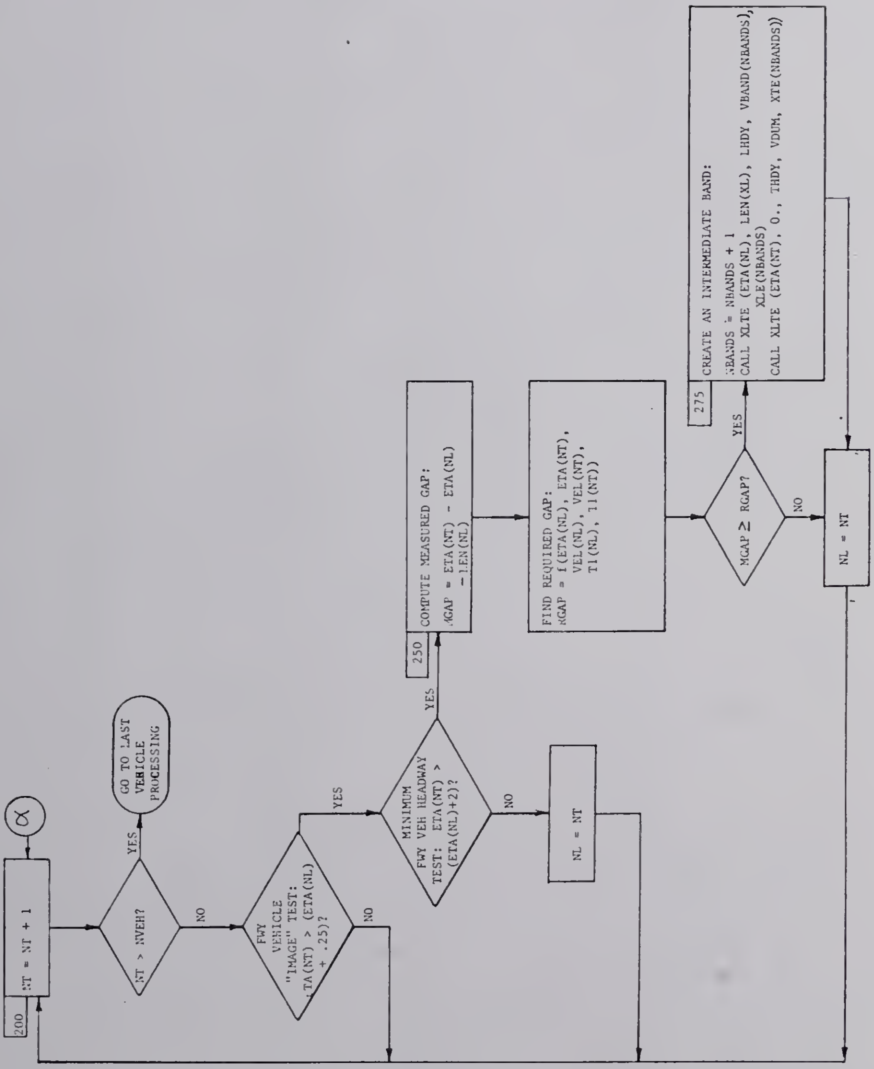
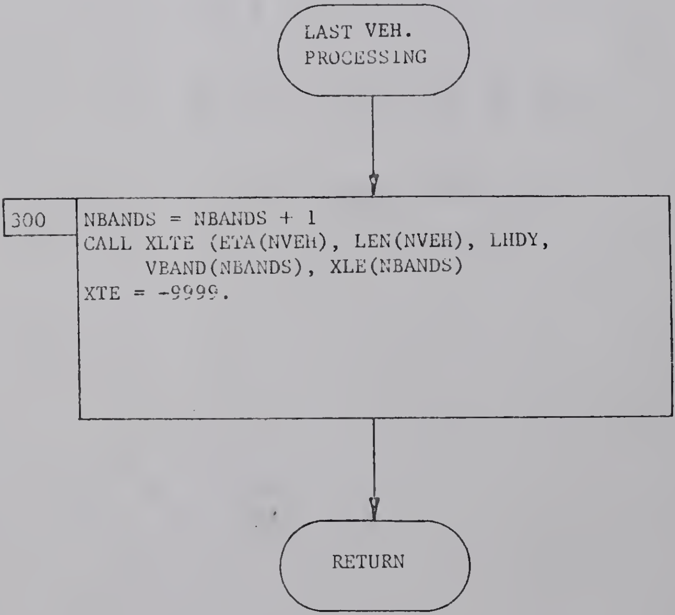

α
200
NT = NT + 1
NT > NVEH?
YES
GO TO LAST VEHICLE PROCESSING
NO
FWY VEHICLE "IMAGE" TEST: ETA(NT) > (ETA(NL) + .25)?
NO
YES
MINIMUM FWY VEH HEADWAY TEST: ETA(NT) > (ETA(NL)+2)?
NO
NL = NT
YES
250
COMPUTE MEASURED GAP:
MGAP = ETA(NT) - ETA(NL) - LEN(NL)
FIND REQUIRED GAP:
RGAP = f(ETA(NL), ETA(NT), VEL(NL), VEL(NT), T1(NL), T1(NT))
MGAP ≥ RGAP?
YES
NO
275
CREATE AN INTERMEDIATE BAND:
NBANDS = NBANDS + 1
CALL XLTE (ETA(NL), LEN(XL), LHDY, VBAND(NBANDS), XLE(NBANDS)
CALL XLTE (ETA(NT), 0., THDY, VDUM, XTE(NBANDS))
NL = NT

Figure 58--Continued



```
NBANDS = NBANDS + 1
CALL XLTE (ETA(NVEH), LEN(NVEH), LHDY,
     VBAND(NBANDS), XLE(NBANDS))
XTE = -9999.
```

Figure 58--Continued

senting the total vehicle contents of the individual sensor lists. This action is performed as the last function of the highway vehicle processor routine and allows the green band status routine to scan the overall list in a straightforward manner. Upon each entry to GBS, then, the number of vehicles in this composite freeway vehicle data array is checked to see if there are any vehicles in the upstream section of the freeway. If there are no such vehicles, a flag indicating that the field display should be turned to an all-green condition is set and an immediate return to the executive routine is made.

If there are freeway vehicles upstream of the merge area currently in the lists, as indicated by a value of the total vehicle count greater than or equal to 1, processing continues with one of two differing simulation program response modes. The Woburn Green Band System as described in Chapter 2 had logic in its on-line Green Band Status routine to skip the process of band creation in the moving mode of operation if no new sensor data had been received in the time interval since the last entry to GBS, and this meant that most of the band movements along the ramp display were caused by the actions of the Green Band Update Routine (GBUD) operating on previously established band tables. Movies taken at the Woburn site indicated the existence of band stability problems there, and the simulation program was initially designed to allow this control program option to be studied. Thus, when using the simulator to represent Woburn control system operation, GBS returns to the executive calling routine if no new sensor data have been flagged as ready for use by the ISR.

It is interesting to note that the Woburn fixed-speed green band algorithm gave noticeably smoother results when tested in Tampa with its "do GBS only if new sensor data are available" flag set permanently on. This routine was used to provide system test capabilities while the Tampa variable speed band propagation logic was under development. No mention of experimentation with this section of the control logic appears in the Woburn system documentation [83-85], but its use was probably intended to reduce the computing workloads on the system, as the Woburn computer had approximately half the processing speed of its Tampa counterpart, making program execution time an important design constraint.

Field experimentation with earlier versions of the Tampa Green Band System on-line control program indicated that the use of the variable-speed green band propagation algorithm discussed in Chapter 3 required that the GBS routine be allowed to destroy old bands and create a new set of bands each time it was entered to give the desired smoothness of band movement across the display. Thus, the Woburn "do GBS only if new sensor data are available" flag was set permanently on in the Tampa on-line control software to accomplish this function. Overall band quality was improved on the field display after this change was implemented, but many of the band edges still exhibited the unstable conditions mentioned earlier.

Thus, processing activity continues in the simulated GBS routine with the creation of the first band on the ramp display if either of two conditions are met:

1. A new sensor activity report has now become available (Woburn option), or
2. On every entry to GBS if any freeway vehicles are in the data lists (Tampa option).

The process described in Chapter 3 for the creation of green bands in the Tampa system is implemented by the simulation, and after the first band is created, the number of vehicles is checked to see if it is greater than one. If the answer is yes, processing continues with the creation of intermediate bands for any two successive vehicles in the freeway data lists which pass the required gap tests. When the last vehicle in the list is reached, the last band on the display is created, and the simulated green band status routine returns to the executive program.

The required gap computations for the creation of a green band on the driver display as described in Chapter 2 are implemented in subroutine RAYGAP and function subprograms F2 and F3. The simulation program uses the approximation formulas derived by Raytheon for use in the on-line control programs to compute the time required for vehicles to accelerate from one velocity to another, as these formulas are currently implemented in the on-line Tampa system.

Three other subroutines complete the control program simulator. Subroutine BINØUT is used to print the current contents of each of the seven sensor lists (stations 1 through 7 represent F1 through F7, respectively). Subroutine GBUD is used to propagate bands established by GBS along a simulated field display by using the equations of band motion established in Chapter 2. A band acceleration rate of 3 feet/second^2 is used in the Tampa variable speed band propagation logic. Subroutine XLTE implements the band edge placement computations discussed in Chapter 3 for the Tampa variable-speed moving mode bands.

As is often the case with system modelling activity, the development of the on-line green band control program simulation model provided many useful insights into the operation of the corresponding real-world system. For example, the development of the simulation logic for the highway vehicle processing program brought to light the value of 20.48 seconds for the constant used in the control program for the testing of overtime conditions of freeway vehicles at the next downstream sensor. A comment in the source code for the Woburn on-line control program indicated that this constant represents the time for a freeway vehicle to reach the next downstream sensor while travelling at the rate of 10 feet per second. This parameter value, then, is sub-optimal for normal system operation, as the freeway velocities observed upstream of the Tampa ramp average on the order of 70-80 feet per second, representing a travel time over the 200 feet spacing between the freeway sensors in the range of 2.5 to 2.8 seconds. The selection of this relatively high value for vehicle retention time in the sensor lists can result in the imposition of extra computing workloads on the control computer, as the data in the lists are continually processed during GBS operations, and even though old data are usually filtered out successfully by the program algorithms, all of the list data must be examined at the rate of 100 times/second.

The standard simulation output is in the form of printed tables of vehicle information, band parameters, and sequential lines of output representing bulb commands to the field display. As computer printers usually have a maximum of 132 characters per line, it was not possible to represent a full set of 152 bulbs comprising the Tampa ramp display on a single line of output. To give an overall view of band activity, it was decided to use one character position to represent 2 adjacent 4-foot sections, and thus each line of band output can show up to 76 "G" characters to represent the full 608-foot length of the Tampa display. Actually, 80 positions are used to allow the representation of display lengths up to the full 640-foot display allowed by on-line control program bit assignments (e.g., 10 words of 16 bits each). While the printed band output from the simulation is ideal for detailed comparisons of band activity under various system control strategies, as will be discussed in the next section, it does not give a true measure of the appearance of band dynamics to observers viewing the same information on the field display. Figure 59 illustrates a scheme which could be used to provide this analysis capability.

The simulation program could easily be modified to be run from a CRT-type terminal associated with a time-sharing computer system. Then, as each new line of band output was generated and displayed on the screen, the program would send a special character to the terminal which would be decoded in a simple logic circuit and used to trigger a camera directed at the screen.

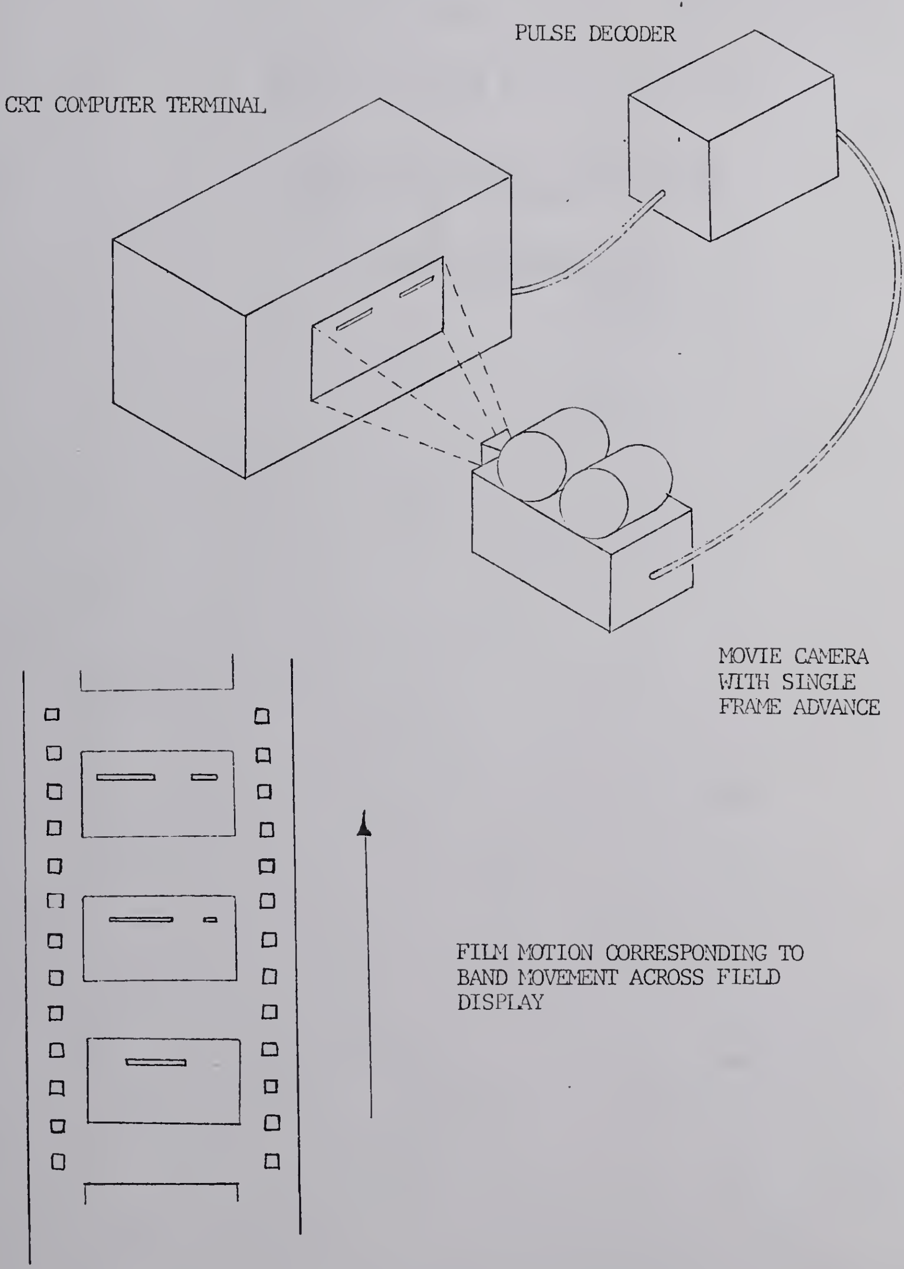


Figure 59. Scheme for Filming Simulated Green Band Outputs

Most teletype-equivalent terminals in current use have a bell character which activates an electronic tone generator, and this could be easily adapted to this application. Then, after an appropriate time delay to allow the exposure of a single film frame to be completed, the simulation program would erase the screen and repeat the process until the specified stopping time of the simulation had been reached. The resulting film could then be played back at a rate corresponding to that representing real-time operation of the system, thus giving an accurate representation of how the bands would appear to ramp drivers.

Another approach for monitoring band activity on a real-time basis from the simulation would be to use a dedicated computer and a high-speed graphics terminal to display the band outputs for direct viewing, but the costs associated with this approach would be extremely high due to the specialized equipment and communications link facilities required. The speed of the simulation model is adequate for such work, as it can operate at approximately twice the speed of the on-line system, primarily due to the fact that the basic vehicle data are supplied as inputs and do not have to be computed from sensor event times.

Analysis of Simulation Results

Freeway data obtained during public operation of the green band system on August 9, 1974, were used to exercise the simulation model. The data tape generated by the on-line program was reduced by the TOGAP software with the punched card output option active, and a deck of sensor report data was produced. This data deck was then used to drive the control program simulation model which generated the results to be discussed in this section.

Initial Processing

Figure 60 shows the input cards as echo-printed by the ISRINI routine. Manual examination of the data deck had noted the time of the first T1 event to be 0.888 seconds into the run, and the simulation start time was specified as 0.850 seconds to avoid unnecessary processing prior to just before the first event. Note that ISRINI reads all of the data cards for the current run at initialization time. These data are loaded into the RAWDAT array discussed earlier, and passed to the simulation at times determined by the updates of the simulated real-time clock.

Figure 60 also includes the output from HVP after it has been called by the simulation monitor at 0.850 seconds into the run. Note that the variable NVEH is zero,

```
TIME=     0.850.ISRINI READING...  7    0.888   1   72.993    0.308    5.475
TIME=     0.850.ISRINI READING...  6    0.914   2   80.000    0.257    7.944
TIME=     0.850.ISRINI READING...  4    2.284   3   63.693    0.295   17.412
TIME=     0.850.ISRINI READING...  7    3.460   2   75.923    0.270    5.192
TIME=     0.850.ISRINI READING...  5    4.088   4   82.645    0.263   13.332
TIME=     0.850.ISRINI READING...  5    5.520   3   63.291    0.373   17.591
TIME=     0.850.ISRINI READING...  6    6.602   4   78.125    0.259   13.821
TIME=     0.850.ISRINI READING...  1    8.666   5   80.000    0.239   20.216
TIME=     0.850.ISRINI READING...  5    8.844   3   58.480    0.357   13.493
TIME=     0.850.ISRINI READING...  7    9.194   4   75.336    0.285   17.962
TIME=     0.850.ISRINI READING...  2   11.162   5   79.365    0.248   28.346
TIME=     0.850.ISRINI READING...  7   12.300   3   57.143    0.377   14.670
TIME=     0.850.ISRINI READING...  3   13.662   5   78.125    0.239   28.561
TIME=     0.850.ISRINI READING...  1   15.636   7   64.935    0.270   39.722
TIME=     0.850.ISRINI READING...  4   16.140   5   78.745    0.214   28.382
TIME=     0.850.ISRINI READING...  1   16.738   8   74.073    0.159   37.852
TIME=     0.850.ISRINI READING...  5   18.538   5   84.031    0.275   27.650
TIME=     0.850.ISRINI READING...  2   18.752   7   62.502    0.290   40.575
TIME=     0.850.ISRINI READING...  2   19.588   8   57.566    0.215   35.776
TIME=     0.850.ISRINI READING...  6   20.962   5   81.466    0.265   27.843
TIME=     0.850.ISRINI READING...  1   21.110   9   79.365    0.230   40.616
TIME=     0.850.ISRINI READING...  3   21.832   7   63.492    0.285   40.273
TIME=     0.850.ISRINI READING...  3   22.634   8   63.292    0.207   41.025
TIME=     0.850.ISRINI READING...  7   23.412   5   81.966    0.267   27.653
TIME=     0.850.ISRINI READING...  2   23.678   9   75.755    0.245   41.583
TIME=     0.850.ISRINI READING...  4   24.946   7   65.360    0.252   39.695
TIME=     0.850.ISRINI READING...  4   25.754   8   55.289    0.183   40.985
TIME=     0.850.ISRINI READING...  3   26.302   9   75.190    0.242   41.783
TIME=     0.850.ISRINI READING...  1   27.690  10   75.760    0.221   46.234
TIME=     0.850.ISRINI READING...  5   27.840   7   71.429    0.320   38.536
TIME=     0.850.ISRINI READING...  5   28.756   8   67.566    0.255   40.063
TIME=     0.850.ISRINI READING...  4   28.906   9   75.186    0.220   41.727
TIME=     0.850.ISRINI READING...  2   30.318  10   75.755    0.231   46.323
TIME=     0.850.ISRINI READING...  6   30.720   7   69.446    0.304   36.841
TIME=     0.850.ISRINI READING...  5   31.448   9   79.365    0.286   41.074
TIME=     0.850.ISRINI READING...  6   31.732   8   67.113    0.241   40.136
TIME=     0.850.ISRINI READING...  3   32.942  10   75.190    0.220   46.423
TIME=     0.850.ISRINI READING...  7   33.635   7   66.495    0.314   36.950
TIME=     0.850.ISRINI READING...  6   34.042   9   75.186    0.284   41.543
TIME=     0.850.ISRINI READING...  7   34.730   8   66.666    0.250   40.190
TIME=     0.850.ISRINI READING...  4   35.544  10   76.333    0.209   48.173
HVP FINISHED AT TIME =     0.850. WITH NVEH =      0
SENSOR BIN   1... NLIST( 1)= 0
SENSOR BIN   2... NLIST( 2)= 0
SENSOR BIN   3... NLIST( 3)= 0
SENSOR BIN   4... NLIST( 4)= 0
SENSOR BIN   5... NLIST( 5)= 0
SENSOR BIN   6... NLIST( 6)= 0
SENSOR BIN   7... NLIST( 7)= 0
TIME=     0.852. NVEH =   0. NLIST=     0    0    0    0    0    0    0
```

Figure 60. Initialization Output from Green Band Simulator

indicating that no freeway vehicles are currently in the system. Also note that the seven sensor lists are empty at this time, as indicated by the values of the NLIST array printed out opposite each list identifier. To review the notational scheme used, BIN 1 represents F1 data, that is, data obtained from the freeway station nearest the merge point location in Tampa (located 384 feet upstream of the merge point). BIN 7 represents data obtained from F7, which is the freeway station most distant from the merge point (located 1,584 feet upstream of the merge point).

The information appearing at the bottom of Figure 60 was printed by the GBS routine, and simply indicates that GBS was entered at 0.852 seconds into the simulation run and that no freeway vehicle data were stored in any of the lists at that time. A note on the simulation program calling sequence is in order at this point. EXEC (MAIN) calls the ISR routine each time the master clock is updated at the 0.002 second cycle rate, or 500 times per simulated second of operation. The routines HVP, GBS, and GBUD are called every five clock updates (0.010 seconds), but these calls are staggered across three successive clock cycles to implement the sequencing logic used in the on-line system. Thus, for the example presented here with the run starting time set to 0.850 seconds, the simulated routine calling times were as follows (all values in simulated system seconds):

ISRINI: 0.850

HVPINI: 0.850

ISR: 0.850, 0.852, 0.854, 0.856, ...

HVP: 0.850, 0.860, 0.870, 0.880, ...

GBS: 0.852, 0.862, 0.872, 0.882, ...

GBUD: 0.854, 0.864, 0.874, 0.884, ...

Simulated Green Band Trajectories

Figure 61 shows slightly over 14 seconds of simulated green band display activity for the data shown in Figure 60. Note that new band information is available every 0.010 seconds from GBUD, and that "normal" band progression is from left to right across the 80 columns of each output line with a monotonic non-decreasing display position for each band edge. The cases where the bands exhibit behavior other than this expected progression on the display are noted in Figure 61 and will be discussed individually below.

Case I: Display Transition from "All Green" Status

Figure 62 shows the detailed simulation outputs which explain the transition of the driver display from an "all green" condition to a state which shows two bands. Note

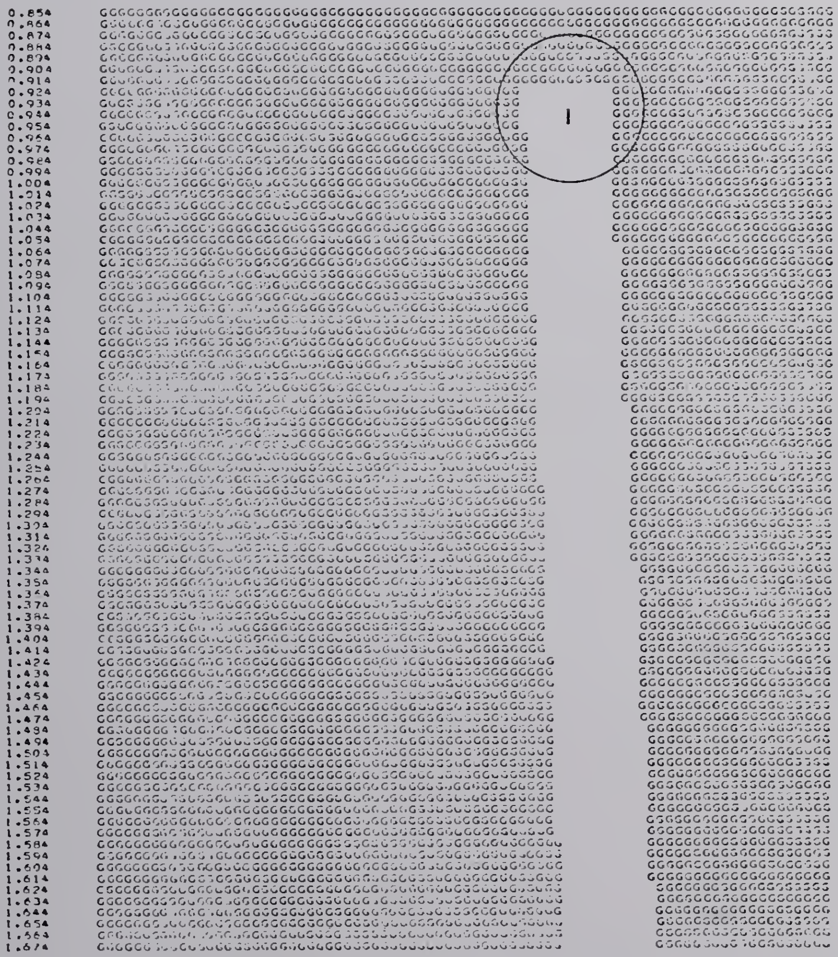


Figure 61. Band Output from Control Program Simulator

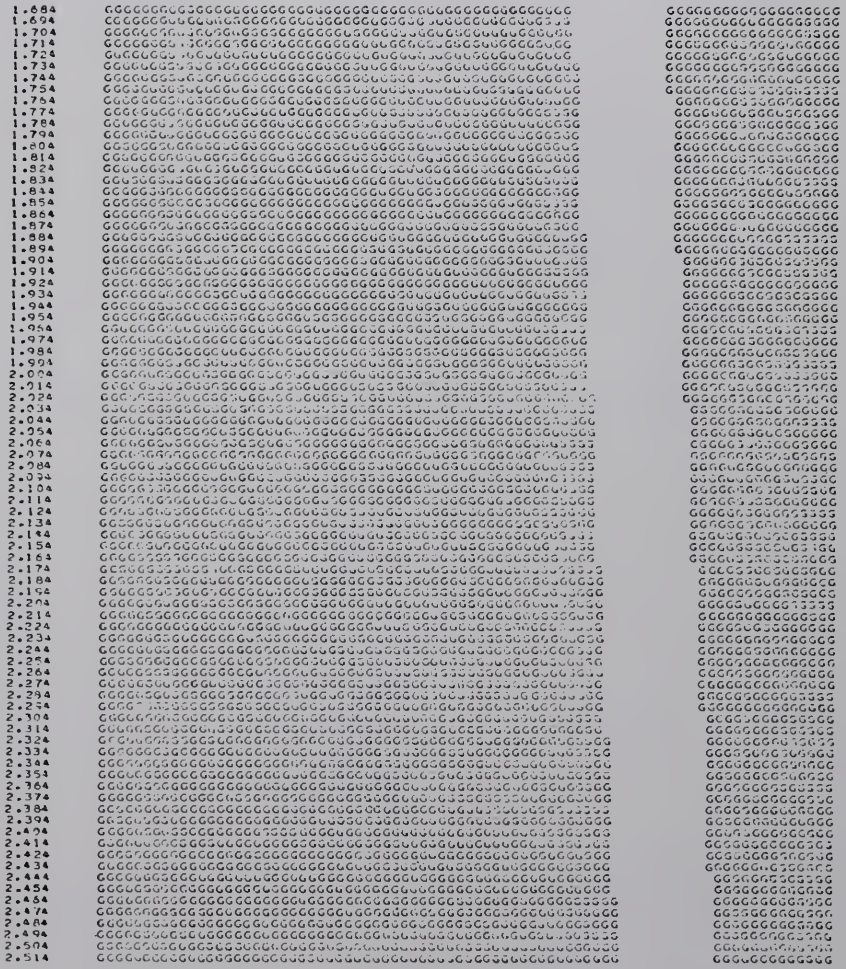


Figure 61--Continued

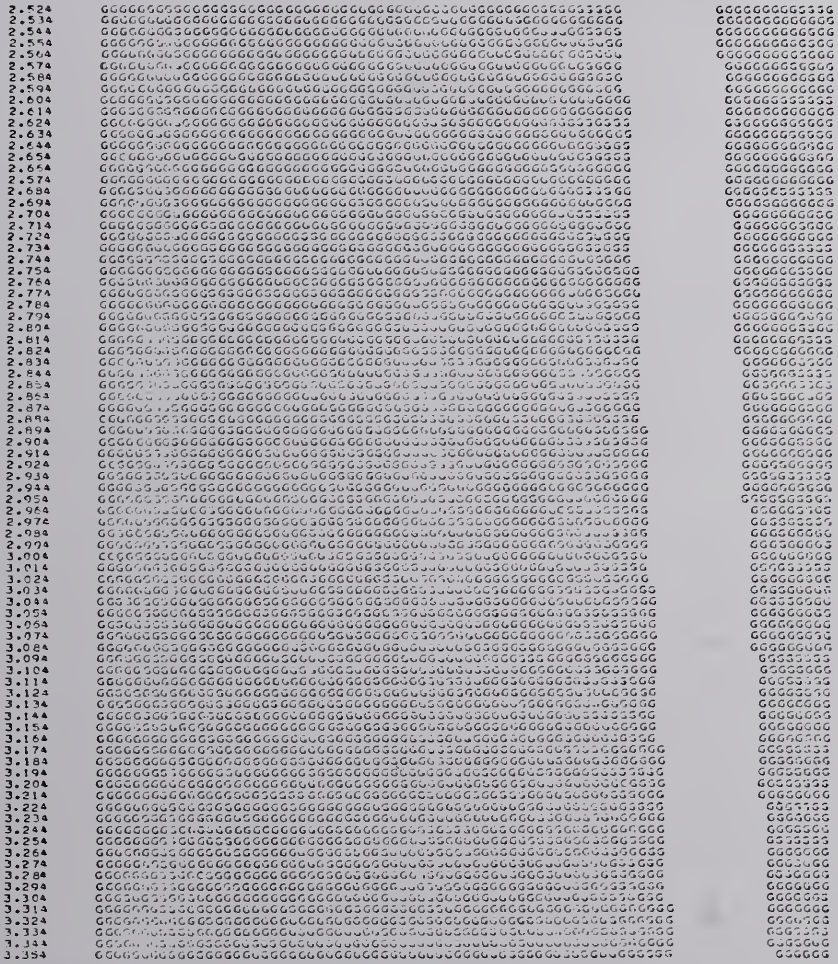


Figure 61--Continued

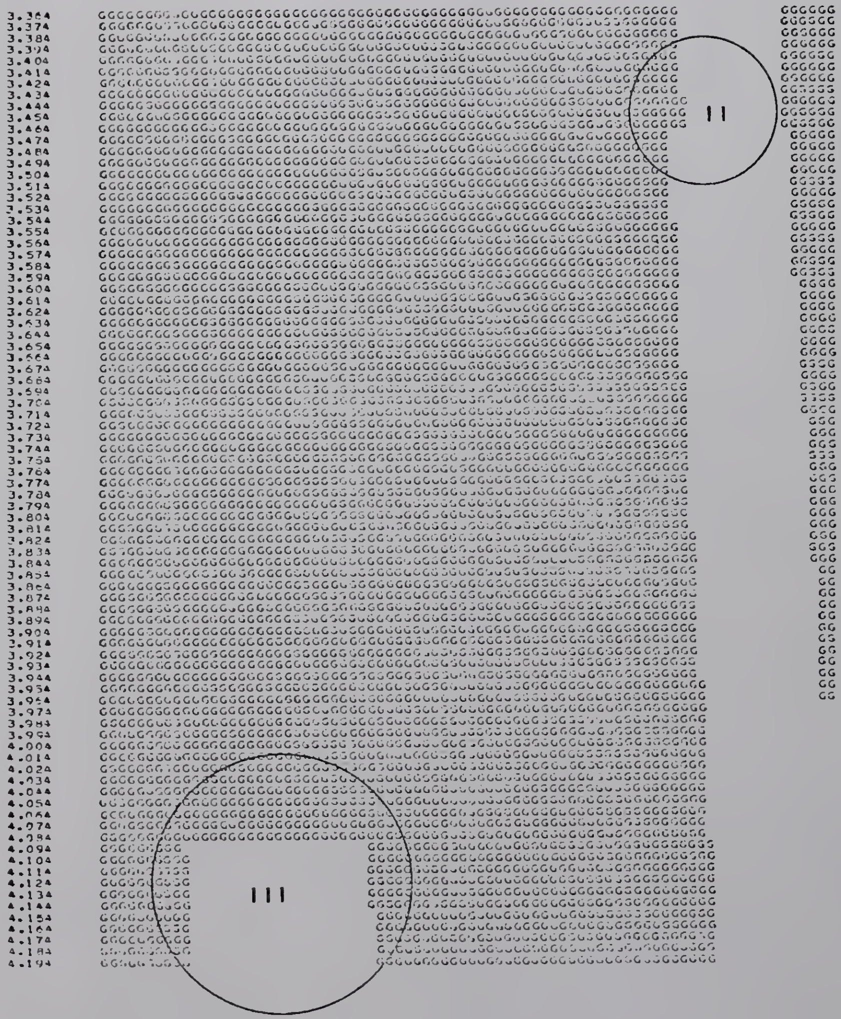


Figure 61--Continued

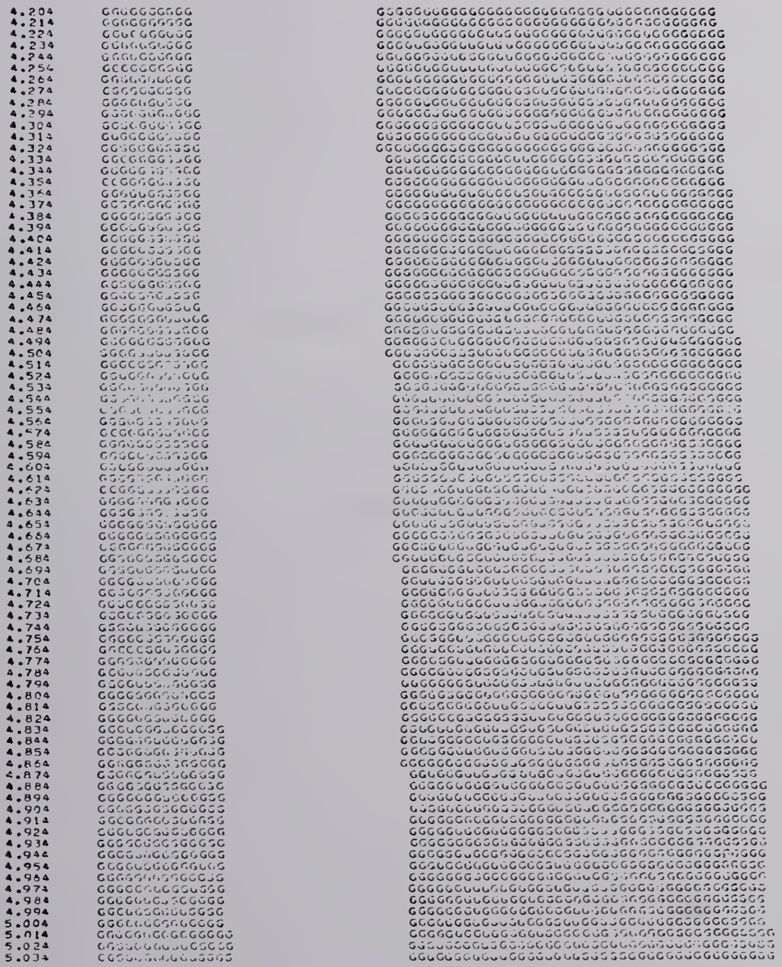


Figure 61--Continued

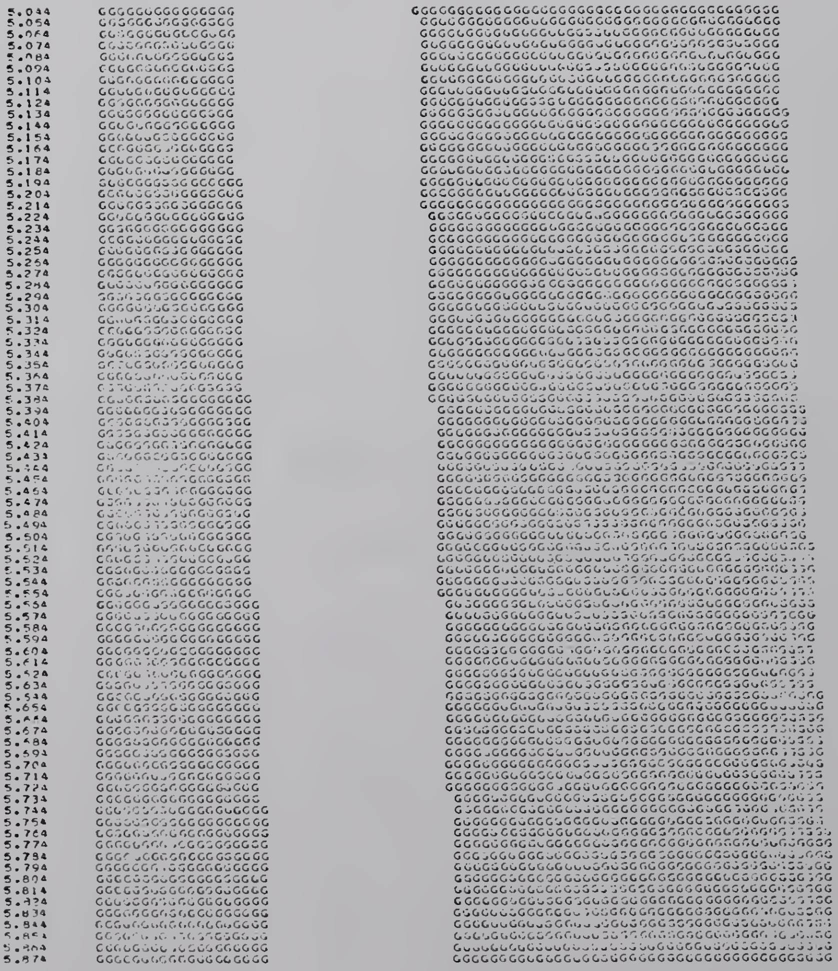


Figure 61--Continued

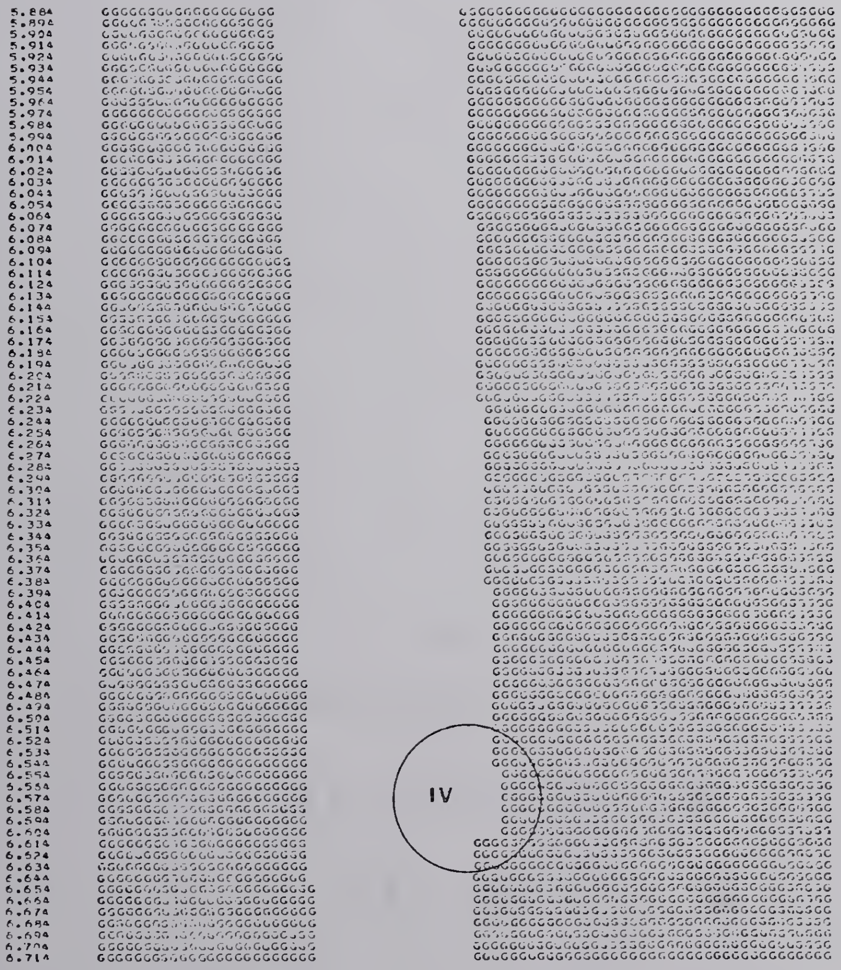


Figure 61--Continued

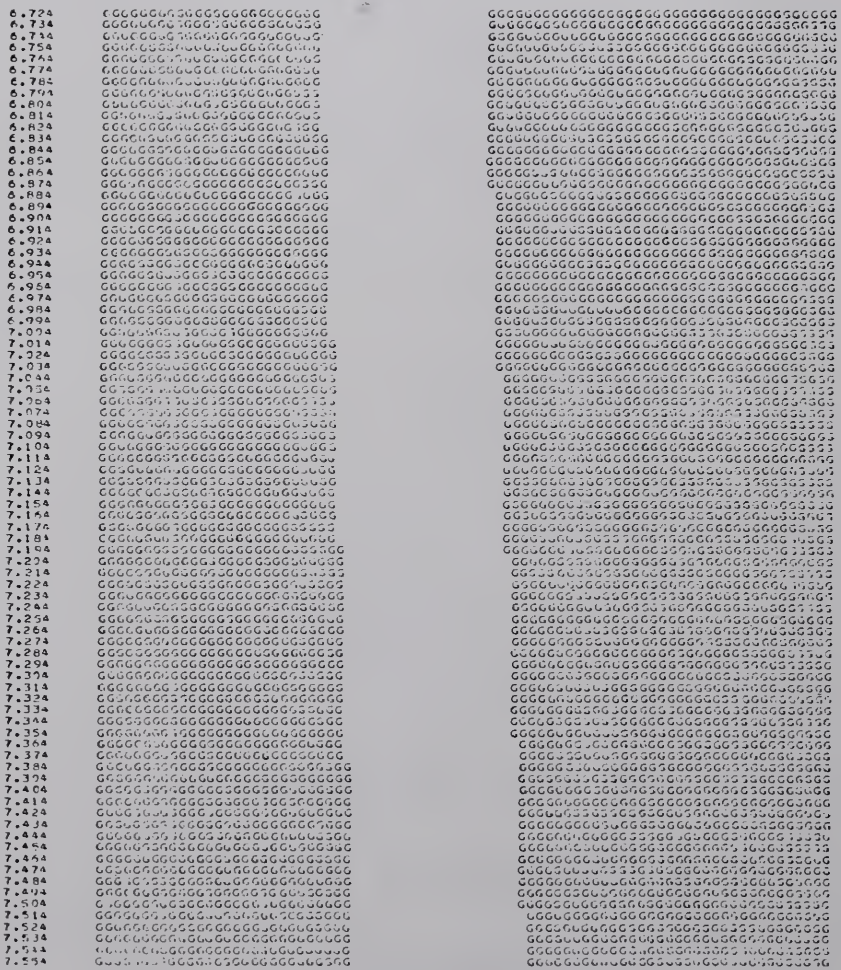


Figure 61--Continued

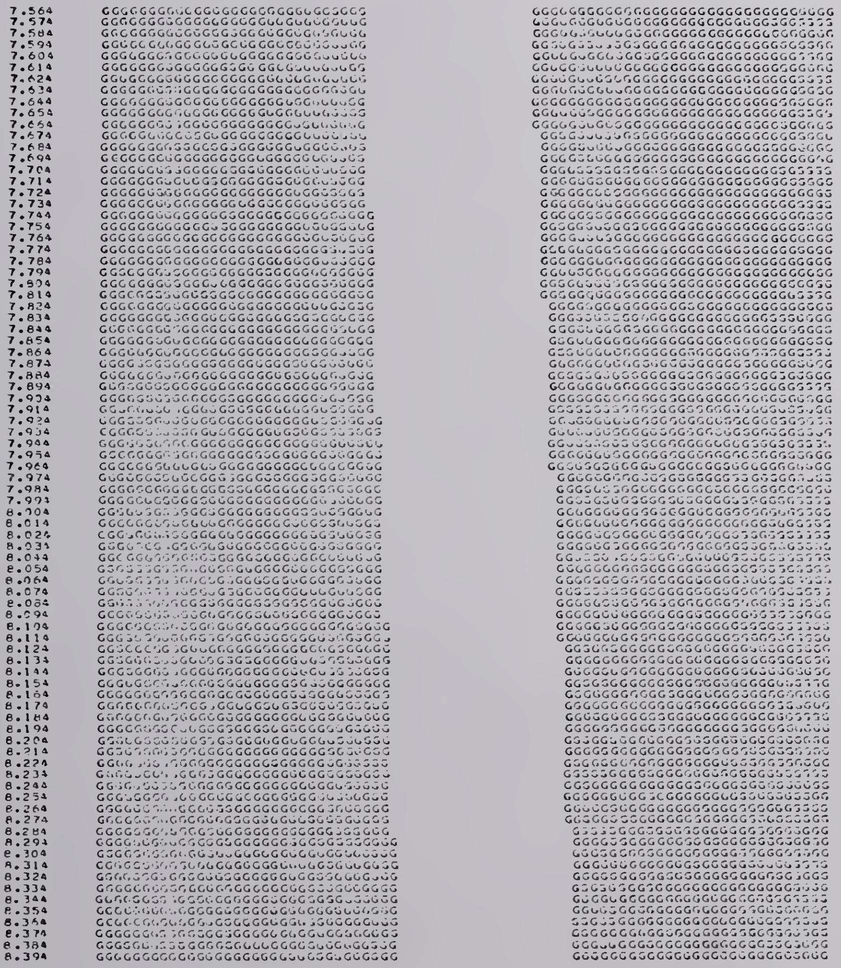


Figure 61--Continued

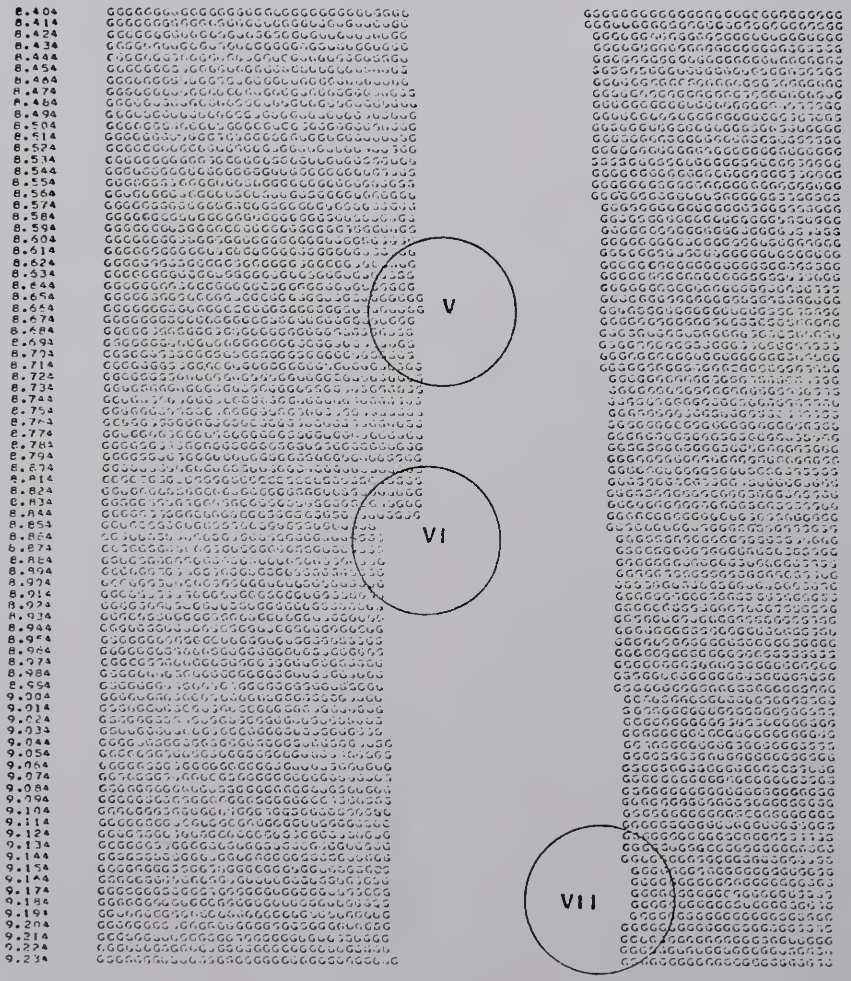


Figure 61--Continued

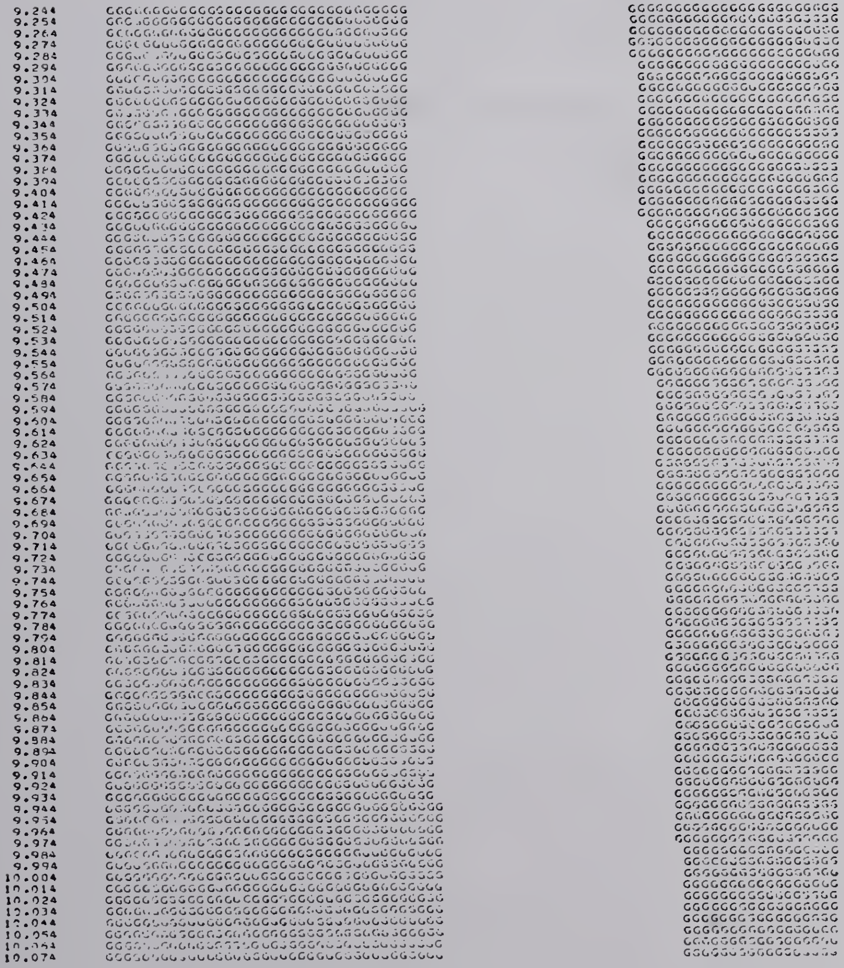


Figure 61--Continued

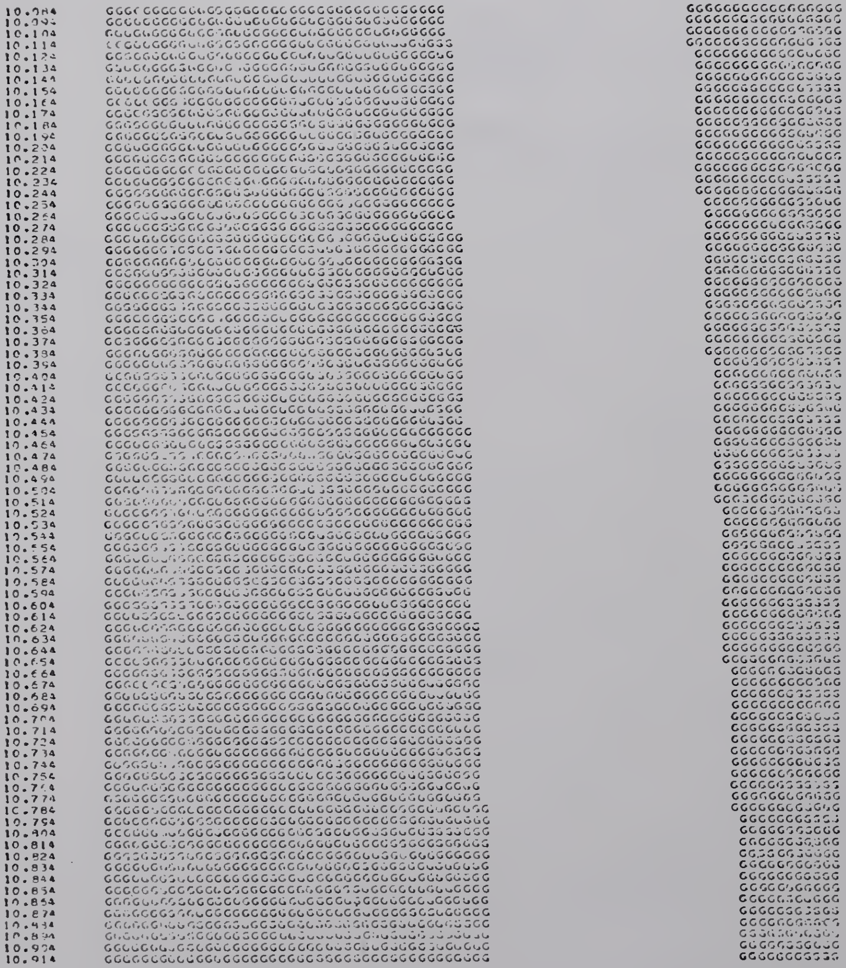


Figure 61--Continued

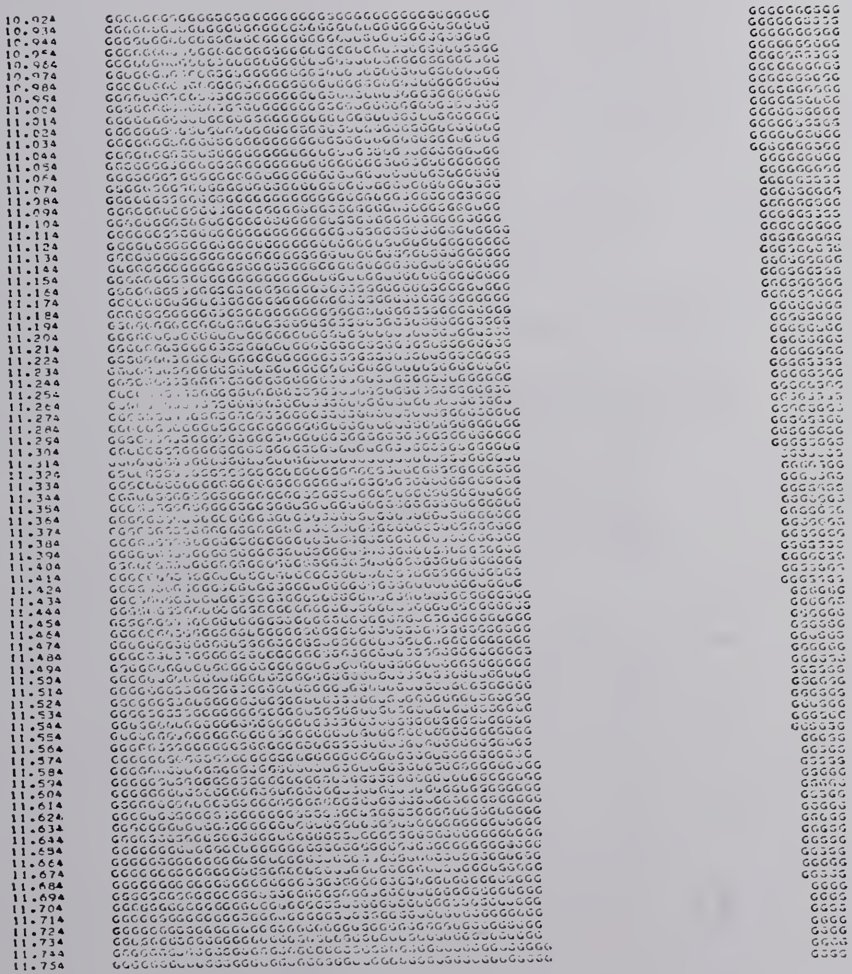


Figure 61--Continued

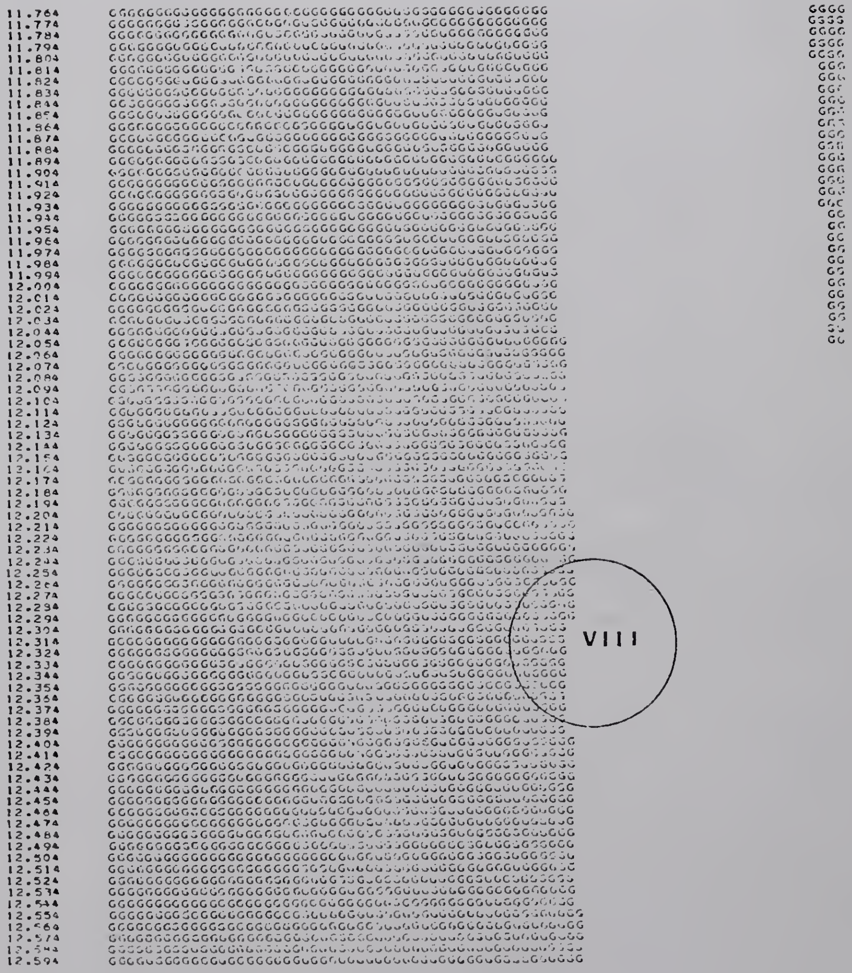


Figure 61--Continued

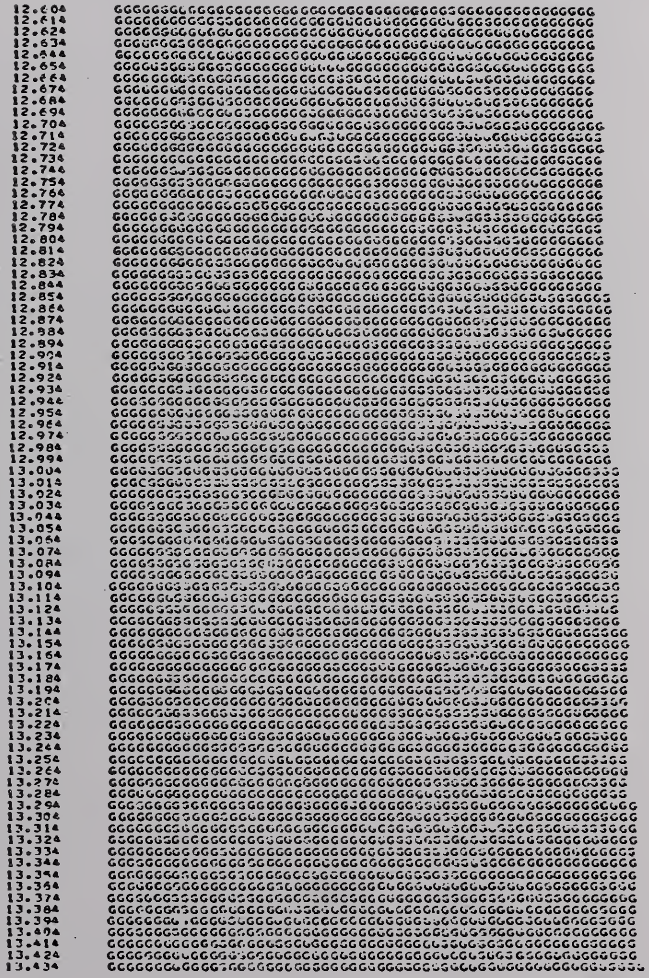


Figure 61--Continued

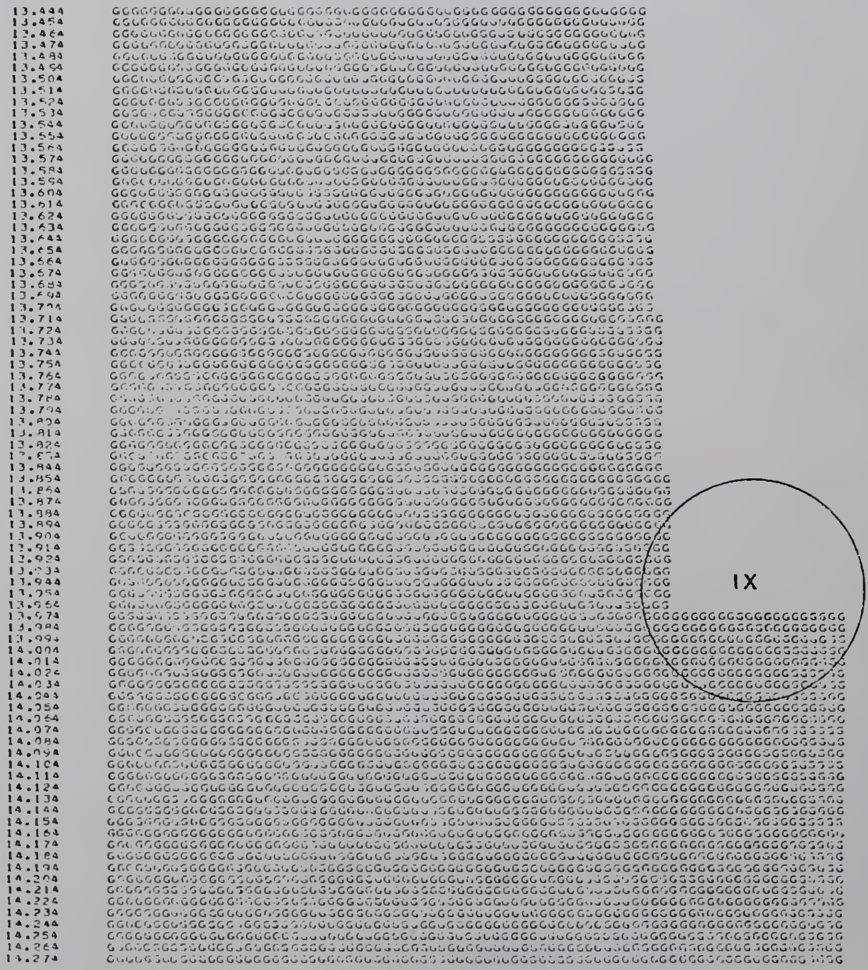


Figure 61--Continued

```
HVP FINISHED AT TIME =      0.880, WITH NVEH =     0
SENSOR BIN  1... NLIST( 1)= 0
SENSOR BIN  2... NLIST( 2)= 0
SENSOR BIN  3... NLIST( 3)= 0
SENSOR BIN  4... NLIST( 4)= 0
SENSOR BIN  5... NLIST( 5)= 0
SENSOR BIN  6... NLIST( 6)= 0
SENSOR BIN  7... NLIST( 7)= 0
TIME=    0.882, NVEH =   0, NLIST=     0     0     0     0     0     0     0

HVP FINISHED AT TIME =      0.890, WITH NVEH =     1
SENSOR BIN  1... NLIST( 1)= 1
VEH. NO. =  1, ETA,T1,VEL,LEN,CARID=      5.875      0.888      72.993      0.308    1.
SENSOR BIN  2... NLIST( 2)= 0
SENSOR BIN  3... NLIST( 3)= 0
SENSOR BIN  4... NLIST( 4)= 0
SENSOR BIN  5... NLIST( 5)= 0
SENSOR BIN  6... NLIST( 6)= 0
SENSOR BIN  7... NLIST( 7)= 0
TIME=    0.892, NVEH =   1, NLIST=      1     0     0     0     0     0     0
FWY VEH NO.  1 ...         5.875        0.888        72.993        0.308     1
TIME=    0.892,GBS FINISHED WITH NBANDS =      2
BAND NO.  1 ...          0.892      -55.481     454.362      844.000          -1.000
BAND NO.  2 ...          0.892      -56.958   -9999.000      482.034           5.875

HVP FINISHED AT TIME =      0.900, WITH NVEH =     1
SENSOR BIN  1... NLIST( 1)= 1
VEH. NO. =  1, ETA,T1,VEL,LEN,CARID=      5.875      0.888      72.993      0.308    1.
SENSOR BIN  2... NLIST( 2)= 0
SENSOR BIN  3... NLIST( 3)= 0
SENSOR BIN  4... NLIST( 4)= 0
SENSOR BIN  5... NLIST( 5)= 0
SENSOR BIN  6... NLIST( 6)= 0
SENSOR BIN  7... NLIST( 7)= 0
TIME=    0.902, NVEH =   1, NLIST=      1     0     0     0     0     0     0
FWY VEH NO.  1 ...         5.875        0.888        72.993        0.308     1
TIME=    0.902,GBS FINISHED WITH NBANDS =      2
BAND NO.  1 ...          0.902      -55.511     454.917      844.000          -1.000
BAND NO.  2 ...          0.902      -56.988   -9999.000      482.604           5.875

HVP FINISHED AT TIME =      0.910, WITH NVEH =     1
SENSOR BIN  1... NLIST( 1)= 1
VEH. NO. =  1, ETA,T1,VEL,LEN,CARID=      5.875      0.888      72.993      0.308    1.
SENSOR BIN  2... NLIST( 2)= 0
SENSOR BIN  3... NLIST( 3)= 0
SENSOR BIN  4... NLIST( 4)= 0
SENSOR BIN  5... NLIST( 5)= 0
SENSOR BIN  6... NLIST( 6)= 0
SENSOR BIN  7... NLIST( 7)= 0
TIME=    0.912, NVEH =   1, NLIST=      1     0     0     0     0     0     0
FWY VEH NO.  1 ...         5.875        0.888        72.993        0.308     1
TIME=    0.912,GBS FINISHED WITH NBANDS =      2
BAND NO.  1 ...          0.912      -55.541     455.473      844.000          -1.000
BAND NO.  2 ...          0.912      -57.018   -9999.000      483.174           5.875

HVP FINISHED AT TIME =      0.920, WITH NVEH =     2
SENSOR BIN  1... NLIST( 1)= 1
VEH. NO. =  1, ETA,T1,VEL,LEN,CARID=      5.875      0.888      72.993      0.308    1.
SENSOR BIN  2... NLIST( 2)= 1
VEH. NO. =  1, ETA,T1,VEL,LEN,CARID=      7.964      0.914      80.000      0.257    2.
SENSOR BIN  3... NLIST( 3)= 0
SENSOR BIN  4... NLIST( 4)= 0
SENSOR BIN  5... NLIST( 5)= 0
SENSOR BIN  6... NLIST( 6)= 0
SENSOR BIN  7... NLIST( 7)= 0
TIME=    0.922, NVEH =   2, NLIST=      1     1     0     0     0     0     0
FWY VEH NO.  1 ...         5.875        0.888        72.993        0.308     1
FWY VEH NO.  2 ...         7.964        0.914        80.000        0.257     2
TIME=    0.922, TVEH,LVEH,MGAP,FGAP...  2  1         1.781         3.864
TIME=    0.922,GBS FINISHED WITH NBANDS =      2
BAND NO.  1 ...          0.922      -55.571     456.028      844.000          -1.000
BAND NO.  2 ...          0.922      -50.933   -9999.000      373.700           7.964
```

Figure 62. Case I Data

that at time 0.890 seconds, HVP has processed the first freeway vehicle detection and inserted the vehicle data into sensor bin 1 (e.g., the first vehicle to be detected was at F1). GBS detected the fact that NVEH was no longer zero when it was entered at 0.902 seconds, and created a "first band" on the display with a leading placement at 844 feet and a trailing edge location at 454.917 feet on the display. NVEH was 1, so GBS went directly to the last vehicle processing logic and created a "last band" using the same freeway vehicle as before. The parameters of the second band were such that it overlapped the first band, and the display remained "all green" at time 0.904 seconds when the two bands were displayed via GBUD. At time 0.912 seconds, GBS was entered again, and the bands associated with the single freeway vehicle were updated. The overlapping condition remained in effect and the displayed information did not change.

At the GBS entry at 0.922 seconds, however, a new freeway vehicle had been detected, and the processing logic for intra-vehicluar gaps was activated. Note that the new freeway detection was at F2, and represented an ETA at the merge point of 7.964 seconds. GBS recognized that the ETA spread between these two vehicles passed the minimum spacing requirement of 2.0 seconds, and proceeded to conduct a required gap analysis. As shown on the printout, the required gap was computed to be 3.864 seconds, and the measured gap, defined as trailing vehicle ETA minus leading vehicle ETA minus leading vehicle length (in seconds), was found to be 1.781 seconds. Thus, no intermediate band was created, and GBS created a "last band" for the display, this time however, using the new freeway vehicle as the leading edge determinant. The first and last display bands did not overlap for this new situation, and GBUD displayed the two distinct bands to the simulated output when it was next entered at time 0.924 seconds.

Case II: A Displayed Band Edge Moves Backward

Figure 63 shows the data associated with the band size reduction which can be seen at time 3.474 seconds on the simulated display. Note that at time 3.462 seconds, GBS was working with three vehicles, and had two legitimate bands on the display (e.g., bands with leading and trailing edges in the range of 0 to 608 feet). At time 3.472 seconds, GBS was entered and discovered four freeway vehicles in the sensor lists, including the previous entries and a new downstream detection for one of the earlier upstream detections. The new data were associated with a vehicle which had originally been detected at F2 with an ETA of 7.964 seconds, and then was noted as passing F1 with a merge ETA of 8.192 seconds. GBS scanned the new freeway list and rejected the old data for the most recent detection through the use of

```
HVP FINISHED AT TIME =     3.460, WITH NVEH =     3
SENSOR BIN   1... NLIST( 1)= 1
VEH. NO. =   1, ETA,T1,VEL,LEN,CARID=       5.875      0.888     72.993      0.308    1.
SENSOR BIN   2... NLIST( 2)= 1
VEH. NO. =   1, ETA,T1,VEL,LEN,CARID=       7.964      0.914     80.000      0.257    2.
SENSOR BIN   3... NLIST( 3)= 0
SENSOR BIN   4... NLIST( 4)= 1
VEH. NO. =   1, ETA,T1,VEL,LEN,CARID=      17.612      2.284     62.893      0.295    3.
SENSOR BIN   5... NLIST( 5)= 0
SENSOR BIN   6... NLIST( 6)= 0
SENSOR BIN   7... NLIST( 7)= 0
TIME=     3.462, NVEH =    3, NLIST=     1    1    0    1    0    0    0
FWY VEH NO.  1 ...        5.875       0.888       72.993      0.308    1
FWY VEH NO.  2 ...        7.964       0.914       80.000      0.257    2
FWY VEH NO.  3 ...       17.612       2.284       62.893      0.295    3
TIME=     3.462, TVEH,LVEH,MGAP,RGAP...  2  1        1.781       3.864
TIME=     3.462, TVEH,LVEH,MGAP,RGAP...  3  2        9.391       6.738
TIME=     3.462,GBS FINISHED WITH NBANDS =      3
BAND NO.  1 ...         3.462     -63.191     606.857     844.000      -1.000       5.875
BAND NO.  2 ...         3.462     -58.553      29.045     512.748       7.964      17.612
BAND NO.  3 ...         3.462      44.000   -9999.000      51.283      17.612      -1.000

HVP FINISHED AT TIME =     3.470, WITH NVEH =     4
SENSOR BIN   1... NLIST( 1)= 2
VEH. NO. =   1, ETA,T1,VEL,LEN,CARID=       5.875      0.888     72.993      0.308    1.
VEH. NO. =   2, ETA,T1,VEL,LEN,CARID=       8.192      3.460     76.923      0.270    2.
SENSOR BIN   2... NLIST( 2)= 1
VEH. NO. =   1, ETA,T1,VEL,LEN,CARID=       7.964      0.914     80.000      0.257    2.
SENSOR BIN   3... NLIST( 3)= 0
SENSOR BIN   4... NLIST( 4)= 1
VEH. NO. =   1, ETA,T1,VEL,LEN,CARID=      17.612      2.284     62.893      0.295    3.
SENSOR BIN   5... NLIST( 5)= 0
SENSOR BIN   6... NLIST( 6)= 0
SENSOR BIN   7... NLIST( 7)= 0
TIME=     3.472, NVEH =    4, NLIST=     2    1    0    1    0    0    0
FWY VEH NO.  1 ...        5.875       0.888       72.993      0.308    1
FWY VEH NO.  2 ...        8.192       3.460       76.923      0.270    2
FWY VEH NO.  3 ...        7.964       0.914       80.000      0.257    2
FWY VEH NO.  4 ...       17.612       2.284       62.893      0.295    3
TIME=     3.472, TVEH,LVEH,MGAP,RGAP...  2  1        2.009       3.746

TIME=     3.472, TVEH,LVEH,MGAP,RGAP...  4  2        9.150       6.678
TIME=     3.472,GBS FINISHED WITH NBANDS =      3
BAND NO.  1 ...         3.472     -63.221     607.489     844.000      -1.000       5.875
BAND NO.  2 ...         3.472     -57.560      29.485     499.302       8.192      17.612
BAND NO.  3 ...         3.472      44.000   -9999.000      51.723      17.612      -1.000
```

Figure 63. Case II Data

the 0.25-second image test discussed previously. The second band on the display was based on the new data therefore, and the band edge moved backward on the display due to the higher ETA value associated with the new detection (e.g., the arrival time of the band at the merge point would also need to be higher in value, or later in time).

Case III: A Band Breaks into Smaller Bands

The display activity at time 4.094 seconds is representative of what happens in the on-line system operation when a freeway vehicle enters the upstream section at a sensor other than the normal entry point at F7. In this case, a new vehicle was seen for the first time at F3, and required the insertion of a blank area on the display to account for its presence. Figure 64 shows the data representing the new vehicle entry. Note particularly the change in the parameters of band number 2.

Case IV: A Displayed Band Edge Moves Backward

Note the regression of the trailing edge of the first band on the display at time 6.614 seconds. What happened here is explained by the data in Figure 65. New data became available on the vehicle originally detected at F3

```
HVP FINISHED AT TIME =      4.080, WITH NVEH =      4
SENSOR BIN   1... NLIST( 1)= 2
VEH. NO. =   1, ETA,T1,VEL,LEN,CARID=      5.875       0.888       72.993       0.308     1.
VEH. NO. =   2, ETA,T1,VEL,LEN,CARID=      8.192       3.460       76.923       0.270     2.
SENSOR BIN   2... NLIST( 2)= 1
VEH. NO. =   1, ETA,T1,VEL,LEN,CARID=      7.964       0.914       80.000       0.257     2.
SENSOR BIN   3... NLIST( 3)= 0
SENSOR BIN   4... NLIST( 4)= 1
VEH. NO. =   1, ETA,T1,VEL,LEN,CARID=     17.612       2.284       62.893       0.295     3.
SENSOR BIN   5... NLIST( 5)= 0
SENSOR BIN   6... NLIST( 6)= 0
SENSOR BIN   7... NLIST( 7)= 0
TIME=    4.082, NVEH =    4, NLIST=      2      1      0      1      0      0      0
FWY VEH NO.   1 ...        5.875       0.888        72.993        0.308      1
FWY VEH NO.   2 ...        8.192       3.460        76.923        0.270      2
FWY VEH NO.   3 ...        7.964       0.914        80.000        0.257      2
FWY VEH NO.   4 ...       17.612       2.284        62.893        0.295      3
TIME=    4.082, TVEH,LVEH,MGAP,FGAP...   2   1          2.009          3.745
TIME=    4.082, TVEH,LVEH,MGAP,FGAP...   4   2          9.150          6.678
TIME=    4.082,GRS FINISHED WITH NBANDS =          3
BAND NO.   1 ...        4.082      -65.051      646.611      844.000      -1.000         5.875
BAND NO.   2 ...        4.082      -59.690       56.325      535.155       8.192        17.612
BAND NO.   3 ...        4.082       44.000    -9999.000       78.563      17.612        -1.000

HVP FINISHED AT TIME =      4.090, WITH NVEH =      5
SENSOR BIN   1... NLIST( 1)= 2
VEH. NO. =   1, ETA,T1,VEL,LEN,CARID=      5.875       0.888       72.993       0.308     1.
VEH. NO. =   2, ETA,T1,VEL,LEN,CARID=      8.192       3.460       76.923       0.270     2.
SENSOR BIN   2... NLIST( 2)= 1
VEH. NO. =   1, ETA,T1,VEL,LEN,CARID=      7.964       0.914       80.000       0.257     2.
SENSOR BIN   3... NLIST( 3)= 1
VEH. NO. =   1, ETA,T1,VEL,LEN,CARID=     13.332       4.088       82.645       0.263     4.
SENSOR BIN   4... NLIST( 4)= 1
VEH. NO. =   1, ETA,T1,VEL,LEN,CARID=     17.612       2.284       62.893       0.295     3.
SENSOR BIN   5... NLIST( 5)= 0
SENSOR BIN   6... NLIST( 6)= 0
SENSOR BIN   7... NLIST( 7)= 0
TIME=    4.092, NVEH =    5, NLIST=      2      1      1      1      0      0      0
FWY VEH NO.   1 ...        5.875       0.888        72.993        0.308      1
FWY VEH NO.   2 ...        8.192       3.460        76.923        0.270      2
FWY VEH NO.   3 ...        7.964       0.914        80.000        0.257      2
FWY VEH NO.   4 ...       13.332       4.088        82.645        0.263      4
FWY VEH NO.   5 ...       17.612       2.284        62.893        0.295      3
TIME=    4.092, TVEH,LVEH,MGAP,RGAP...   2   1          2.009          3.746
TIME=    4.092, TVEH,LVEH,MGAP,RGAP...   4   2          4.870          3.762
TIME=    4.092, TVEH,LVEH,MGAP,RGAP...   5   4          4.017          6.683
TIME=    4.092,GRS FINISHED WITH NBANDS =          3
BAND NO.   1 ...        4.092      -65.081      647.262      844.000      -1.000         5.875
BAND NO.   2 ...        4.092      -59.720      245.034      535.752       8.192        13.332
BAND NO.   3 ...        4.092       44.000    -9999.000       79.003      17.612        -1.000
```

Figure 64.   Case III Data

```
HVP FINISHED AT TIME =      6.600, WITH NVEH =      5
SENSOR BIN   1... NLIST( 1)= 1
VEH. NO. =   1. ETA,T1,VEL,LEN,CARID=      8.192       3.460      76.923      0.270    2.
SENSOR BIN   2... NLIST( 2)= 1
VEH. NO. =   1. ETA,T1,VEL,LEN,CARID=      7.964       0.914      80.000      0.257    2.
SENSOR BIN   3... NLIST( 3)= 2
VEH. NO. =   1. ETA,T1,VEL,LEN,CARID=     13.332       4.088      82.645      0.263    4.
VEH. NO. =   2. ETA,T1,VEL,LEN,CARID=     17.591       5.520      63.291      0.373    3.
SENSOR BIN   4... NLIST( 4)= 1
VEH. NO. =   1. ETA,T1,VEL,LEN,CARID=     17.612       2.284      62.893      0.295    3.
SENSOR BIN   5... NLIST( 5)= 0
SENSOR BIN   6... NLIST( 6)= 0
SENSOR BIN   7... NLIST( 7)= 0
TIME=      6.602. NVEH =    5. NLIST=      1     1     2     1     0     0     0
FWY VEH NO.  1 ...        8.192        3.460        76.923        0.270    2
FWY VEH NO.  2 ...        7.964        0.914        80.000        0.257    2
FWY VEH NO.  3 ...       13.332        4.088        82.645        0.263    4
FWY VEH NO.  4 ...       17.591        5.520        63.291        0.373    3
FWY VEH NO.  5 ...       17.612        2.284        62.893        0.295    3
TIME=     6.602. TVEH,LVEH,MGAP,RGAP...   3  1          4.870         3.762
TIME=     6.602. TVEH,LVEH,MGAP,RGAP...   4  3          3.996         5.742
TIME=     6.602,GBS FINISHED WITH NBANDS =        3
BAND NO.  1 ...         6.602      -65.660      659.879      844.000      -1.000       8.192
BAND NO.  2 ...         6.602       56.000      362.014      694.840       8.192      13.332
BAND NO.  3 ...         6.602       44.000    -9999.000      189.443      17.612      -1.000

HVP FINISHED AT TIME =      6.610. WITH NVEH =      6
SENSOR BIN   1... NLIST( 1)= 1
VEH. NO. =   1. ETA,T1,VEL,LEN,CARID=      8.192       3.460      76.923      0.270    2.
SENSOR BIN   2... NLIST( 2)= 2
VEH. NO. =   1. ETA,T1,VEL,LEN,CARID=      7.964       0.914      80.000      0.257    2.
VEH. NO. =   2. ETA,T1,VEL,LEN,CARID=     13.621       6.602      78.125      0.269    4.
SENSOR BIN   3... NLIST( 3)= 2
VEH. NO. =   1. ETA,T1,VEL,LEN,CARID=     13.332       4.088      82.645      0.263    4.
VEH. NO. =   2. ETA,T1,VEL,LEN,CARID=     17.591       5.520      63.291      0.373    3.
SENSOR BIN   4... NLIST( 4)= 1
VEH. NO. =   1. ETA,T1,VEL,LEN,CARID=     17.612       2.284      62.893      0.295    3.
SENSOR BIN   5... NLIST( 5)= 0
SENSOR BIN   6... NLIST( 6)= 0
SENSOR BIN   7... NLIST( 7)= 0
TIME=      6.612. NVEH =    6. NLIST=      1     2     2     1     0     0     0
FWY VEH NO.  1 ...        8.192        3.460        76.923        0.270    2
FWY VEH NO.  2 ...        7.964        0.914        80.000        0.257    2
FWY VEH NO.  3 ...       13.821        6.602        78.125        0.269    4
FWY VEH NO.  4 ...       13.332        4.088        82.645        0.263    4
FWY VEH NO.  5 ...       17.591        5.520        63.291        0.373    3
FWY VEH NO.  6 ...       17.612        2.284        62.893        0.295    3
TIME=     6.612. TVEH,LVEH,MGAP,RGAP...   3  1          5.359         3.926
TIME=     6.612. TVEH,LVEH,MGAP,RGAP...   5  3          3.501         5.957
TIME=     6.612.GBS FINISHED WITH NBANDS =        3
BAND NO.  1 ...         6.612      -65.690      660.535      844.000      -1.000       8.192
BAND NO.  2 ...         6.612       66.000      338.293      695.500       8.192      13.821
BAND NO.  3 ...         6.612       44.000    -9999.000      189.883      17.612      -1.000
```

Figure 65. Case IV Data

with an ETA of 13.332 seconds. The detection at F2 indicated an ETA of 13.821 seconds, and the band edge moved back to reflect the higher expected travel time associated with the new detection.

Case V: A New Vehicle Enters the Upstream Freeway Section

The band shrink at time 8.674 seconds can be explained by the data shown in Figure 66. Note that a new vehicle detection at F7 was processed by HVP at 8.670 seconds, and this new vehicle became the trailing vehicle for the second band, now defined by vehicles with ETA values of 17.591 and 28.216 seconds.

Case VI: A Substantial Band Size Reduction

Simulation data in Figure 67 indicate the cause of the upstream movement of the leading edge of band number 2 at 8.854 seconds. New data on vehicle number 3 (e.g., the TOGAP vehicle identification code number 3, shown at the extreme right of the bin outputs) became available at time 8.844 seconds, and HVP placed it in the freeway lists at time 8.850 seconds. Note that after this update, HVP has now stored information on vehicle number 3 taken at F4, F3, and F2. The band perturbation is a result of the use of the most recent ETA value for vehicle 3 of 18.488 seconds, as

```
HVP FINISHED AT TIME =      8.660, WITH NVEH =     4
 SENSOR BIN   1... NLIST( 1)= 0
 SENSOR BIN   2... NLIST( 2)= 1
VEH. NO. =  1, ETA,T1,VEL,LEN,CARID=     13.821      6.602     78.125     0.269    4.
SENSOR BIN  3... NLIST( 3)= 2
VEH. NO. =  1, ETA,T1,VEL,LEN,CARID=     13.332      4.088     82.645     0.263    4.
VEH. NO. =  2, ETA,T1,VEL,LEN,CARID=     17.591      5.520     63.291     0.373    3.
SENSOR BIN  4... NLIST( 4)= 1
VEH. NO. =  1, ETA,T1,VEL,LEN,CARID=     17.612      2.284     62.893     0.295    3.
SENSOR BIN  5... NLIST( 5)= 0
SENSOR BIN  6... NLIST( 6)= 0
SENSOR BIN  7... NLIST( 7)= 0
TIME=      8.662, NVEH =    4, NLIST=      0     1     2     1     0     0     0
FWY  VEH NO.  1 ...        13.821       6.602       78.125      0.269    4
FWY  VEH NO.  2 ...        13.332       4.088       82.645      0.263    4
FWY  VEH NO.  3 ...        17.591       5.520       63.291      0.373    3
FWY  VEH NO.  4 ...        17.612       2.284       62.893      0.295    3
TIME=      8.662, TVEH,LVEH,MGAP,RGAP...   3   1       3.501       5.957
TIME=      8.662,GBS FINISHED WITH NBANDS =       2
BAND NO.  1 ...        8.662      -54.953     444.644     844.000      -1.000      13.821
BAND NO.  2 ...        8.662      -45.097   -9999.000     280.283      17.612      -1.000

HVP FINISHED AT TIME =      8.670, WITH NVEH =     5
SENSOR BIN   1... NLIST( 1)= 0
SENSOR BIN   2... NLIST( 2)= 1
VEH. NO. =  1, ETA,T1,VEL,LEN,CARID=     13.821      6.602     78.125     0.269    4.
SENSOR BIN  3... NLIST( 3)= 2
VEH. NO. =  1, ETA,T1,VEL,LEN,CARID=     13.332      4.088     82.645     0.263    4.
VEH. NO. =  2, ETA,T1,VEL,LEN,CARID=     17.591      5.520     63.291     0.373    3.
SENSOR BIN  4... NLIST( 4)= 1
VEH. NO. =  1, ETA,T1,VEL,LEN,CARID=     17.612      2.284     62.893     0.295    3.
SENSOR BIN  5... NLIST( 5)= 0
SENSOR BIN  6... NLIST( 6)= 0
SENSOR BIN  7... NLIST( 7)= 1
VEH. NO. =  1, ETA,T1,VEL,LEN,CARID=     28.216      8.666     80.000     0.239    5.
TIME=      8.672, NVEH =    5, NLIST=      0     1     2     1     0     0     1
FWY  VEH NO.  1 ...        13.821       6.602       78.125      0.269    4
FWY  VEH NO.  2 ...        13.332       4.088       82.645      0.263    4
FWY  VEH NO.  3 ...        17.591       5.520       63.291      0.373    3
FWY  VEH NO.  4 ...        17.612       2.284       62.893      0.295    3
FWY  VEH NO.  5 ...        28.216       8.666       80.000      0.239    5
TIME=      8.672, TVEH,LVEH,MGAP,FGAP...   3   1       3.501       5.957
TIME=      8.672, TVEH,LVEH,MGAP,FGAP...   5   3      10.252       7.518
TIME=      8.672,GBS FINISHED WITH NBANDS =       3
BAND NO.  1 ...        8.672      -54.983     445.194     844.000      -1.000      13.821
BAND NO.  2 ...        8.672      -44.954    -208.290     278.141      17.591      28.216
BAND NO.  3 ...        8.672       44.000   -9999.000    -183.606      28.216      -1.000
```

Figure 66. Case V Data

```
HVP FINISHED AT TIME =      8.340, WITH NVEH =      5
SENSOR BIN   1... NLIST( 1)= 0
SENSOR BIN   2... NLIST( 2)= 1
VEH. NO. =   1, ETA,T1,VEL,LEN,CARID=     13.821      6.602      78.125      0.269    4.
SENSOR BIN   3... NLIST( 3)= 2
VEH. NO. =   1, ETA,T1,VEL,LEN,CARID=     13.332      4.088      82.645      0.263    4.
VEH. NO. =   2, ETA,T1,VEL,LEN,CARID=     17.591      5.520      63.291      0.373    3.
SENSOR BIN   4... NLIST( 4)= 1
VEH. NO. =   1, ETA,T1,VEL,LEN,CARID=     17.612      2.284      62.893      0.295    3.
SENSOR BIN   5... NLIST( 5)= 0
SENSOR BIN   6... NLIST( 6)= 0
SENSOR BIN   7... NLIST( 7)= 1
VEH. NO. =   1, ETA,T1,VEL,LEN,CARID=     28.215      8.666      80.000      0.239    5.
TIME=    8.842, NVEH =    5, NLIST=     0      1      2      1      0      0      1
FWY VEH NO.  1 ...         13.821      6.602      78.125      0.269    4
FWY VEH NO.  2 ...         13.332      4.088      82.645      0.263    4
FWY VEH NO.  3 ...         17.591      5.520      63.291      0.373    3
FWY VEH NO.  4 ...         17.612      2.284      62.893      0.295    3
FWY VEH NO.  5 ...         28.216      8.666      80.000      0.239    5
TIME=    8.842, TVEH,LVEH,MGAP,RGAP...    3    1        3.501      5.957
TIME=    8.842, TVEH,LVEH,MGAP,RGAP...    5    3       10.252      7.518
TIME=    8.842,GBS FINISHED WITH NBANDS =     3
BAND NO.  1 ...        8.842    -55.493     454.584     844.000      -1.000      13.821
BAND NO.  2 ...        8.842    -45.464    -200.810     285.826      17.591      28.216
BAND NO.  3 ...        8.842     44.000   -9999.000    -176.126      28.216      -1.000

HVP FINISHED AT TIME =      8.850, WITH NVEH =      6
SENSOR BIN   1... NLIST( 1)= 0
SENSOR BIN   2... NLIST( 2)= 2
VEH. NO. =   1, ETA,T1,VEL,LEN,CARID=     13.821      6.602      78.125      0.269    4.
VEH. NO. =   2, ETA,T1,VEL,LEN,CARID=     18.488      8.844      58.480      0.357    3.
SENSOR BIN   3... NLIST( 3)= 2
VEH. NO. =   1, ETA,T1,VEL,LEN,CARID=     13.332      4.088      82.645      0.263    4.
VEH. NO. =   2, ETA,T1,VEL,LEN,CARID=     17.591      5.520      63.291      0.373    3.
SENSOR BIN   4... NLIST( 4)= 1
VEH. NO. =   1, ETA,T1,VEL,LEN,CARID=     17.612      2.284      62.893      0.295    3.
SENSOR BIN   5... NLIST( 5)= 0
SENSOR BIN   6... NLIST( 6)= 0
SENSOR BIN   7... NLIST( 7)= 1
VEH. NO. =   1, ETA,T1,VEL,LEN,CARID=     28.216      8.666      80.000      0.239    5.
TIME=    8.852, NVEH =    6, NLIST=     0      2      2      1      0      0      1
FWY VEH NO.  1 ...         13.821      6.602      78.125      0.269    4
FWY VEH NO.  2 ...         18.488      8.844      58.480      0.357    3

FWY VEH NO.  3 ...         13.332      4.088      82.645      0.263    4
FWY VEH NO.  4 ...         17.591      5.520      63.291      0.373    3
FWY VEH NO.  5 ...         17.612      2.284      62.893      0.295    3
FWY VEH NO.  6 ...         28.216      8.666      80.000      0.239    5
TIME=    8.852, TVEH,LVEH,MGAP,RGAP...    2    1        4.398      5.794
TIME=    8.852, TVEH,LVEH,MGAP,RGAP...    6    2        9.371      7.901
TIME=    8.852,GBS FINISHED WITH NBANDS =     3
BAND NO.  1 ...        8.852    -55.523     455.139     844.000      -1.000      13.821
BAND NO.  2 ...        8.852     44.000    -200.370     247.136      18.488      28.216
BAND NO.  3 ...        8.852     44.000   -9999.000    -175.686      28.216      -1.000
```

Figure 67. Case VI Data

opposed to the use of the previous ETA estimate of 17.591 seconds during the last cycle.

Case VII: A Displayed Band Edge Moves Backward

This case is similar to the last case presented. As the data in Figure 68 shows, HVP has added new data to the sensor lists at time 9.200 seconds, representing a downstream detection of TOGAP vehicle number 4. As the ETA of the vehicle increased from its old value, the band moved back to allow a greater travel time to the merge point location.

Case VIII: A Displayed Band Edge Moves Backward

As before, new vehicle data at a downstream sensor cause a band jump upstream on the display. In this case, represented by the data in Figure 69, the control system has new data available on TOGAP vehicle number 3 at F1, and the ETA update is some 0.182 seconds higher than the old value. Note that at this point in time, the HVP operating constants were such that the freeway data lists contained three detection reports of vehicle number 4, four detection reports of vehicle number 3, and two detection reports of vehicle number 5.

```
HVP FINISHED AT TIME =       9.190. WITH NVEH =      6
SENSOR BIN  1... NLIST( 1)= 0
SENSOR BIN  2... NLIST( 2)= 2
VEH. NO. =  1. ETA.T1.VEL.LEN.CARID=     13.821      6.602     78.125      0.269    4.
VEH. NO. =  2. ETA.T1.VEL.LEN.CARID=     18.488      8.844     58.480      0.357    3.
SENSOR BIN  3... NLIST( 3)= 2
VEH. NO. =  1. ETA.T1.VEL.LEN.CARID=     13.332      4.088     82.645      0.263    4.
VEH. NO. =  2. ETA.T1.VEL.LEN.CARID=     17.591      5.520     63.291      0.373    3.
SENSOR BIN  4... NLIST( 4)= 1
VEH. NO. =  1. ETA.T1.VEL.LEN.CARID=     17.612      2.284     62.893      0.295    3.
SENSOR BIN  5... NLIST( 5)= 0
SENSOR BIN  6... NLIST( 6)= 0
SENSOR BIN  7... NLIST( 7)= 1
VEH. NO. =  1. ETA.T1.VEL.LEN.CARID=     28.216      8.666     80.000      0.239    5.
TIME=     9.192. NVEH =   6. NLIST=     0     2     2     1     0     0     1
FWY VEH NO.  1 ...           13.821      6.602      78.125        0.269   4
FWY VEH NO.  2 ...           18.488      8.844      58.480        0.357   3
FWY VEH NO.  3 ...           13.332      4.088      82.645        0.263   4
FWY VEH NO.  4 ...           17.591      5.520      63.291        0.373   3
FWY VEH NO.  5 ...           17.612      2.284      62.893        0.295   3
FWY VEH NO.  6 ...           28.216      8.666      80.000        0.239   5
TIME=     9.192. TVEH.LVEH.MGAP.RGAP...   2  1          4.398        5.794
TIME=     9.192. TVEH.LVEH.MGAP.RGAP...   6  2          9.371        7.901
TIME=     9.192.GBS FINISHED WITH NBANDS =       3
BAND NO.  1 ...          9.192     -56.543     474.191     844.000      -1.000      13.821
BAND NO.  2 ...          9.192      44.000    -185.411     262.096      18.488      28.216
BAND NO.  3 ...          9.192      44.000   -9999.000    -160.726      28.216      -1.000

HVP FINISHED AT TIME =       9.200. WITH NVEH =      7
SENSOR BIN  1... NLIST( 1)= 1
VEH. NO. =  1. ETA.T1.VEL.LEN.CARID=     13.962      9.194     76.336      0.285    4.
SENSOR BIN  2... NLIST( 2)= 2
VEH. NO. =  1. ETA.T1.VEL.LEN.CARID=     13.821      6.602     78.125      0.269    4.
VEH. NO. =  2. ETA.T1.VEL.LEN.CARID=     18.488      8.844     58.480      0.357    3.
SENSOR BIN  3... NLIST( 3)= 2
VEH. NO. =  1. ETA.T1.VEL.LEN.CARID=     13.332      4.088     82.645      0.263    4.
VEH. NO. =  2. ETA.T1.VEL.LEN.CARID=     17.591      5.520     63.291      0.373    3.
SENSOR BIN  4... NLIST( 4)= 1
VEH. NO. =  1. ETA.T1.VEL.LEN.CARID=     17.612      2.284     62.893      0.295    3.
SENSOR BIN  5... NLIST( 5)= 0
SENSOR BIN  6... NLIST( 6)= 0
SENSOR BIN  7... NLIST( 7)= 1
VEH. NO. =  1. ETA.T1.VEL.LEN.CARID=     28.216      8.666     80.000      0.239    5.
TIME=     9.202. NVEH =   7. NLIST=     1     2     2     1     0     0     1
FWY VEH NO.  1 ...           13.962      9.194      76.336        0.285   4
FWY VEH NO.  2 ...           13.821      6.602      78.125        0.269   4
FWY VEH NO.  3 ...           18.488      8.844      58.480        0.357   3
FWY VEH NO.  4 ...           13.332      4.088      82.645        0.263   4
FWY VEH NO.  5 ...           17.591      5.520      63.291        0.373   3
FWY VEH NO.  6 ...           17.612      2.284      62.893        0.295   3
FWY VEH NO.  7 ...           28.216      8.666      80.000        0.239   5
TIME=     9.202. TVEH.LVEH.MGAP.RGAP...   3  1          4.241        5.609
TIME=     9.202. TVEH.LVEH.MGAP.RGAP...   7  3          9.371        7.901
TIME=     9.202.GBS FINISHED WITH NBANDS =       3
BAND NO.  1 ...          9.202     -56.150     466.809     844.000      -1.000      13.962
BAND NO.  2 ...          9.202      44.000    -184.970     262.536      18.488      28.216
BAND NO.  3 ...          9.202      44.000   -9999.000    -160.286      28.216      -1.000
```

Figure 68. Case VII Data

```
HVP FINISHED AT TIME =     12.290, WITH NVEH =      8
SENSOR BIN  1... NLIST( 1)= 1
VEH. NO. =  1, ETA,T1,VEL,LEN,CARID=     13.962       9.194      76.336       0.285    4.
SENSOR BIN  2... NLIST( 2)= 2
VEH. NO. =  1, ETA,T1,VEL,LEN,CARID=     13.821       6.602      78.125       0.269    4.
VEH. NO. =  2, ETA,T1,VEL,LEN,CARID=     18.488       8.844      58.480       0.357    3.
SENSOR BIN  3... NLIST( 3)= 2
VEH. NO. =  1, ETA,T1,VEL,LEN,CARID=     13.332       4.088      82.645       0.263    4.
VEH. NO. =  2, ETA,T1,VEL,LEN,CARID=     17.591       5.520      63.291       0.373    3.
SENSOR BIN  4... NLIST( 4)= 1
VEH. NO. =  1, ETA,T1,VEL,LEN,CARID=     17.612       2.284      62.893       0.295    3.
SENSOR BIN  5... NLIST( 5)= 0
SENSOR BIN  6... NLIST( 6)= 1
VEH. NO. =  1, ETA,T1,VEL,LEN,CARID=     28.348      11.162      79.365       0.248    5.
SENSOR BIN  7... NLIST( 7)= 1
VEH. NO. =  1, ETA,T1,VEL,LEN,CARID=     28.216       8.665      80.000       0.239    5.
TIME=    12.292, NVEH =    8, NLIST=      1     2     2     1     0     1     1
FWY VEH NO.  1 ...          13.962         9.194         76.336         0.285     4
FWY VEH NO.  2 ...          13.821         6.602         78.125         0.269     4
FWY VEH NO.  3 ...          18.488         8.844         58.480         0.357     3
FWY VEH NO.  4 ...          13.332         4.088         82.645         0.263     4
FWY VEH NO.  5 ...          17.591         5.520         63.291         0.373     3
FWY VEH NO.  6 ...          17.612         2.284         62.893         0.295     3
FWY VEH NO.  7 ...          28.348        11.162         79.365         0.248     5
FWY VEH NO.  8 ...          28.216         8.666         80.000         0.239     5
TIME=    12.292, TVEH,LVEH,MGAP,RGAP...  3  1        4.241           5.609
TIME=    12.292, TVEH,LVEH,MGAP,RGAP...  7  3        9.503           7.740
TIME=    12.292,GBS FINISHED WITH NBANDS =       3
BAND NO.  1 ...        12.292      -65.420      654.635      844.000       -1.000       13.962
BAND NO.  2 ...        12.292      -53.170      -54.819      412.511       18.488       28.348
BAND NO.  3 ...        12.292       44.000    -9999.000      -24.326       28.216       -1.000

HVP FINISHED AT TIME =     12.300, WITH NVEH =      9
SENSOR BIN  1... NLIST( 1)= 2
VEH. NO. =  1, ETA,T1,VEL,LEN,CARID=     13.962       9.194      76.336       0.285    4.
VEH. NO. =  2, ETA,T1,VEL,LEN,CARID=     18.670      12.300      57.143       0.377    3.
SENSOR BIN  2... NLIST( 2)= 2
VEH. NO. =  1, ETA,T1,VEL,LEN,CARID=     13.821       6.602      78.125       0.269    4.
VEH. NO. =  2, ETA,T1,VEL,LEN,CARID=     18.488       8.844      58.480       0.357    3.
SENSOR BIN  3... NLIST( 3)= 2
VEH. NO. =  1, ETA,T1,VEL,LEN,CARID=     13.332       4.088      82.645       0.263    4.
VEH. NO. =  2, ETA,T1,VEL,LEN,CARID=     17.591       5.520      63.291       0.373    3.
SENSOR BIN  4... NLIST( 4)= 1
VEH. NO. =  1, ETA,T1,VEL,LEN,CARID=     17.612       2.284      62.893       0.295    3.
SENSOR BIN  5... NLIST( 5)= 0
SENSOR BIN  6... NLIST( 6)= 1
VEH. NO. =  1, ETA,T1,VEL,LEN,CARID=     28.348      11.162      79.365       0.248    5.
SENSOR BIN  7... NLIST( 7)= 1
VEH. NO. =  1, ETA,T1,VEL,LEN,CARID=     28.216       8.666      80.000       0.239    5.
TIME=    12.302, NVEH =    9, NLIST=      2     2     2     1     0     1     1
FWY VEH NO.  1 ...          13.962         9.194         76.336         0.285     4
FWY VEH NO.  2 ...          18.670        12.300         57.143         0.377     3
FWY VEH NO.  3 ...          13.821         6.602         78.125         0.269     4
FWY VEH NO.  4 ...          18.488         8.844         58.480         0.357     3
FWY VEH NO.  5 ...          13.332         4.088         82.645         0.263     4
FWY VEH NO.  6 ...          17.591         5.520         63.291         0.373     3
FWY VEH NO.  7 ...          17.612         2.284         62.893         0.295     3
FWY VEH NO.  8 ...          28.348        11.162         79.365         0.248     5
FWY VEH NO.  9 ...          28.216         8.666         80.000         0.239     5
TIME=    12.302, TVEH,LVEH,MGAP,RGAP...  2  1        4.423           4.652
TIME=    12.302, TVEH,LVEH,MGAP,RGAP...  8  2        9.301           6.982
TIME=    12.302,GBS FINISHED WITH NBANDS =       3
BAND NO.  1 ...        12.302      -65.450      655.290      844.000       -1.000       13.962
BAND NO.  2 ...        12.302      -52.595      -54.379      402.378       18.670       28.348
BAND NO.  3 ...        12.302       44.000    -9999.000      -23.887       28.216       -1.000
```

Figure 69. Case VII Data

Case IX: A Displayed Band Jumps to an "All Green" Condition

Note the forward jump of 120.0 feet along the display of the single band at time 13.974 seconds. Figure 70 shows data which explain this event. TOGAP vehicle number 4 had an ETA at merge point of 13.962 seconds when HVP was entered at time 13.960 seconds, but did not qualify as serving in an acceptable gap. At time 13.970 seconds, HVP flagged vehicle 4 as being overtime at the merge point and removed it from the vehicle lists. The vehicles remaining in the sensor bins at that time were positioned such as to cause the formation of overlapping bands which illuminated the entire display.

Simulation of Woburn GBS Control Logic with Tampa's Variable-Speed Bands

Recall the earlier discussion concerning the need for inhibiting the control logic feature in the Woburn GBS routine which prevented the formation of new band placement data unless new sensor data were available. To illustrate the effects of this change on observed green band quality, a simulation run was made which used the Tampa variable band speed logic and only created new band control information at the times sensor reports were received. Representative results from this run are shown in Figure 71. A comparison of this output with band placements for the same time period

```
HVP FINISHED AT TIME =     13.960, WITH NVEH =      8
SENSOR BIN  1... NLIST( 1)= 2
VEH. NO. =  1, ETA,TI,VEL,LEN,CARID=     13.962       9.194      76.336      0.285   4.

VEH. NO. =  2, ETA,TI,VEL,LEN,CARID=     18.670      12.300      57.143      0.377   3.
SENSOR BIN  2... NLIST( 2)= 1
VEH. NO. =  1, ETA,TI,VEL,LEN,CARID=     18.488       8.844      58.480      0.357   3.
SENSOR BIN  3... NLIST( 3)= 1
VEH. NO. =  1, ETA,TI,VEL,LEN,CARID=     17.591       5.520      63.291      0.373   3.
SENSOR BIN  4... NLIST( 4)= 1
VEH. NO. =  1, ETA,TI,VEL,LEN,CARID=     17.612       2.284      62.893      0.295   3.
SENSOR BIN  5... NLIST( 5)= 1
VEH. NO. =  1, ETA,TI,VEL,LEN,CARID=     28.561      13.662      78.125      0.239   5.
SENSOR BIN  6... NLIST( 6)= 1
VEH. NO. =  1, ETA,TI,VEL,LEN,CARID=     28.348      11.162      79.365      0.248   5.
SENSOR BIN  7... NLIST( 7)= 1
VEH. NO. =  1, ETA,TI,VEL,LEN,CARID=     28.216       8.666      80.000      0.239   5.
TIME=   13.962, NVEH =    8, NLIST=     2     1     1     1     1     1     1
FWY VEH NO.  1 ...        13.962       9.194       76.336       0.285    4
FWY VEH NO.  2 ...        18.670      12.300       57.143       0.377    3
FWY VEH NO.  3 ...        18.488       8.844       58.480       0.357    3
FWY VEH NO.  4 ...        17.591       5.520       63.291       0.373    3
FWY VEH NO.  5 ...        17.612       2.284       62.893       0.295    3
FWY VEH NO.  6 ...        28.561      13.662       78.125       0.239    5
FWY VEH NO.  7 ...        28.348      11.162       79.365       0.248    5
FWY VEH NO.  8 ...        28.216       8.666       80.000       0.239    5
TIME=   13.962, TVEH,LVEH,MGAP,RGAP...  2  1       4.423       4.652
TIME=   13.962, TVEH,LVEH,MGAP,FGAP...  6  2       9.514       6.833
TIME=   13.962,GBS FINISHED WITH NBANDS =     3
BAND NO.  1 ...       13.962      66.000     764.800     844.000      -1.000      13.962
BAND NO.  2 ...       13.962     -57.575       9.289     493.819      18.670      28.561
BAND NO.  3 ...       13.962      44.000   -9999.000      49.153      28.216      -1.000

HVP FINISHED AT TIME =     13.970, WITH NVEH =      7
SENSOR BIN  1... NLIST( 1)= 1
VEH. NO. =  1, ETA,TI,VEL,LEN,CARID=     18.670      12.300      57.143      0.377   3.
SENSOR BIN  2... NLIST( 2)= 1
VEH. NO. =  1, ETA,TI,VEL,LEN,CARID=     18.488       8.844      58.480      0.357   3.
SENSOR BIN  3... NLIST( 3)= 1
VEH. NO. =  1, ETA,TI,VEL,LEN,CARID=     17.591       5.520      63.291      0.373   3.
SENSOR BIN  4... NLIST( 4)= 1
VEH. NO. =  1, ETA,TI,VEL,LEN,CARID=     17.612       2.284      62.893      0.295   3.
SENSOR BIN  5... NLIST( 5)= 1
VEH. NO. =  1, ETA,TI,VEL,LEN,CARID=     28.561      13.662      78.125      0.239   5.
SENSOR BIN  6... NLIST( 6)= 1
VEH. NO. =  1, ETA,TI,VEL,LEN,CARID=     28.348      11.162      79.365      0.248   5.
SENSOR BIN  7... NLIST( 7)= 1
VEH. NO. =  1, ETA,TI,VEL,LEN,CARID=     28.216       8.666      80.000      0.239   5.
TIME=   13.972, NVEH =    7, NLIST=     1     1     1     1     1     1     1
FWY VEH NO.  1 ...        18.670      12.300       57.143       0.377    3
FWY VEH NO.  2 ...        18.488       8.844       58.480       0.357    3
FWY VEH NO.  3 ...        17.591       5.520       63.291       0.373    3
FWY VEH NO.  4 ...        17.612       2.284       62.893       0.295    3
FWY VEH NO.  5 ...        28.561      13.662       78.125       0.239    5
FWY VEH NO.  6 ...        28.348      11.162       79.365       0.248    5
FWY VEH NO.  7 ...        28.216       8.666       80.000       0.239    5
TIME=   13.972, TVEH,LVEH,MGAP,RGAP...  5  1       9.514       6.833
TIME=   13.972,GBS FINISHED WITH NBANDS =     3
BAND NO.  1 ...       13.972     -56.336     470.296     844.000      -1.000      18.670
BAND NO.  2 ...       13.972     -57.605       9.729     494.395      18.670      28.561
BAND NO.  3 ...       13.972      44.000   -9999.000      49.593      28.216      -1.000
```

Figure 70. Case IX Data

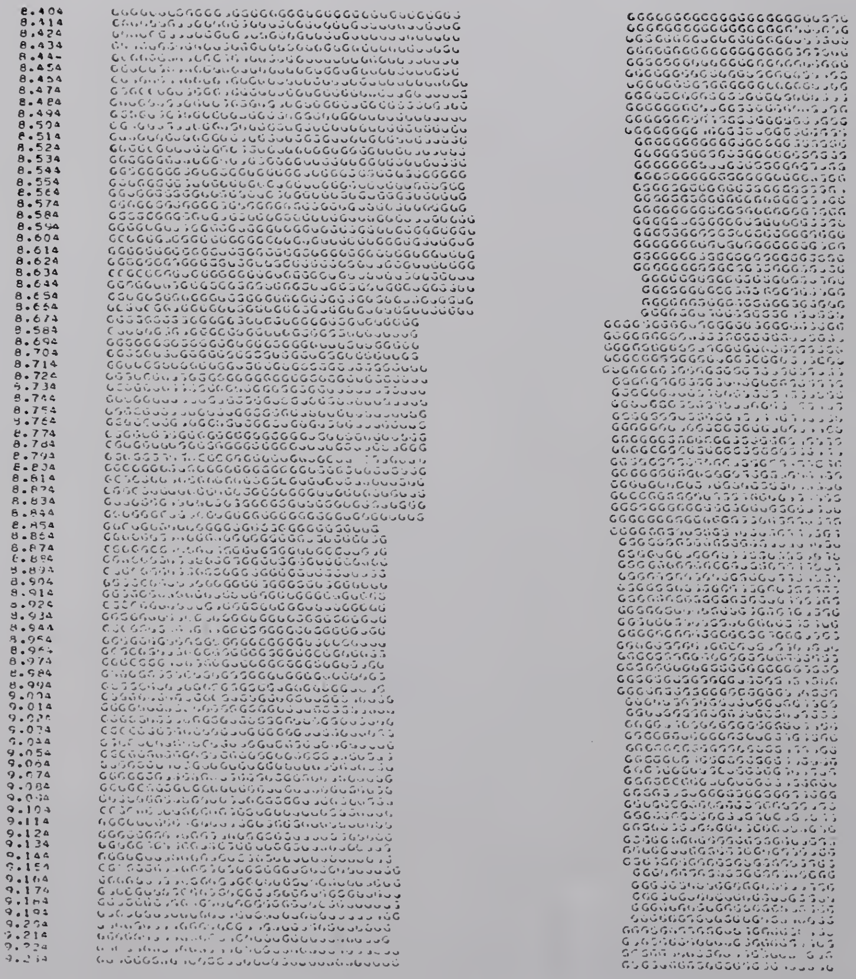


Figure 71. Band Output Showing GBS Operation Inhibited Except at Sensor Event Times

earlier in Figure 61 clearly illustrates the benefits of the "always do GBS" feature of the Tampa system. The explanation for the relatively large band perturbations in the Woburn logic case is related to the lack of precision associated with projecting bands over several seconds of time using simple kinematic expressions in GBUD as opposed to the updating of band control information at a rate of 100 times/second using the GBS processing.

System Design
Implication of Simulation Results

A review of the examples in the previous section representing other than normal band progression across the display indicates that no fundamental design problems exist with the processing algorithms currently implemented in Tampa. All of the band movements on the ramp display generated by the simulation model are in response to the actual freeway environment as reported by field sensor data, and no instances of shortcomings in the logic which cause the generation of false display information have been identified. The instability of bands on the display is simply due to the constantly changing vehicle trajectories in the upstream freeway section. In one sense, then, the quality of information on freeway traffic conditions being presented to ramp drivers through the green band display is too good, e.g., very small changes in measured vehicle characteristics on the freeway are being represented in band perturbations which have no significant potential for assisting the ramp drivers in carrying out the merging maneuver. This latter point is made only with respect to small band perturbations such as those that might result from the system processing a vehicle ETA report which is several tenths of a second different at a downstream station than was originally measured. In the cases of a freeway vehicle "cut-in" at one of the sensor stations, however, the removal or sudden substantial size change of bands currently being displayed is a necessary safety-oriented response by the system, and does provide vital information to ramp drivers.

Given that band instability in response to small freeway vehicle trajectory changes is considered undesirable in future merge systems, several approaches are available for reducing the magnitude of the problem, and the green band control program simulator discussed earlier in this chapter could be easily modified to study these approaches to identify the most promising direction for future research in this area. For example, freeway vehicle velocities, lengths, and estimated times of arrival at the merge point vary as the vehicles pass from station to station through the upstream area as a function of traffic conditions and individual driver characteristics. As the highway vehicle processor in the on-line program does not currently do vehicle tracking, the differing conditions associated with a given vehicle as it passes from one sensor station to the next can, in isolated cases, be interpreted as representing different vehicles in the on-line control system, contributing to the band stability problem. One application of the green band simulation program, therefore, would be to study the implementation of freeway vehicle tracking in the on-line control algorithm, which would use this capability to purge vehicle data from the previous upstream sensor list when an identified vehicle is detected arriving at a given downstream sensor. Although the algorithms required to implement vehicle tracking in the on-line control system would of necessity require extra computational effort above that currently needed by the system, the reduction in the number of vehicles maintained in the on-line sensor lists would partially offset this requirement for extra computing by reducing the number of vehicles that would have to be scanned on each entry to the highway vehicle processing program, and which would subsequently be considered by GBS in the preparation of green band display information.

Another technique for band placement decision logic which could be investigated by the simulation program would consist of classifying freeway vehicle velocities, estimated times of arrival at the merge point, and lengths into classes of such values. This could be done at the most distant upstream sensor, and as each vehicle proceeded downstream through the remaining freeway sensors, its characteristics could be checked at each of the sensors to establish if they still fell within the original categories. If in fact they did, the "vehicle characteristics classification vector" would not be changed and the green band updating would be based on the classifications detected at the original upstream station. This concept would completely eliminate band variations based on small differences in individual vehicle measurements at successive downstream stations. Again, however, the requirement for extra processing in the on-line system above that currently implemented would have to be traded off against the observed reduction in green band perturbations, as additional computing hardware might be required to implement these advanced algorithms.

One final area of potential improvements to green band stability is related to the consideration of the number of freeway sensors used to monitor the section upstream of the ramp. In the limit, if continuous freeway vehicle tracking were possible, band progression across the display could be made as smooth as one desired, as freeway vehicle speeds and positions would continually be available for band placement decisions. In any physical system, however, continuous real-time tracking and band control is not possible, due on one level to the inherent delays and discrete scanning rates associated with sensor hardware, and on another level to the extremely high costs associated with implementing the number of sensors and computing hardware required to even approach a capability for continuous vehicle tracking using conventional traffic sensor hardware.

Any practical moving merge control system, then, represents a design trade-off with respect to the amount of sensor hardware and associated computing equipment needed to prepare the information on freeway conditions which it uses to control the ramp displays. High prediction accuracy and smooth display operation will always cost more to achieve than will lower degrees of prediction accuracy and band stability. Again, the use of a simulation model such as the one discussed earlier would allow proposed merge control design concepts to be evaluated for their ability to meet stated levels of display quality and system performance without incurring the costs associated with prototype tests under field conditions. Final system designs would need field trials, but the range of candidate systems which could be evaluated would be greatly expanded.

Need for Closed-Loop Control of Display Activity in Merging Control Systems

As discussed in Chapter 1, the Pacer moving merge control system represented a closed-loop control philosophy, in which the motions of individual ramp vehicles were tracked and used as one of the inputs to the positioning of pacer lights displaying recommended vehicle trajectories for safe merging maneuvers. The green band system used an open-loop control philosophy which displayed bands on the ramp in response to freeway gap activity only, and did not consider the motions of individual ramp vehicles. Observations of the operations of the Tampa Green Band System have led to the following considerations relating to a need for "partially" closing the loop in the band propagation algorithm by displaying bands only when vehicles are on the ramp and are safely able to use them:

1. Driver confidence in the system could possibly be enhanced by providing green bands only when a vehicle is on the ramp, thus leading ramp drivers to the conclusion that the system is in fact able to detect their presence and is considering it in programming the merge maneuver.

2. Green bands in the current Tampa system and in its earlier Woburn counterpart are gener-

ated in response to freeway gaps only, and do not consider motions or the absence of motions of ramp vehicles on the ramp, e.g., bands are propagated continually in the moving mode of operation even when ramp vehicles are stopped on the ramp. Thus, green bands under these conditions can lead the drivers of upstream ramp vehicles into the rear end of stopped vehicles on the ramp, creating a potential safety hazard. The related problem of green band propagation into stopped vehicles in the merge area has been solved in the Tampa system by the use of the band masking logic based on merge area presence detector occupancy as discussed in Chapter 3. This concept of band masking in response to the detection of stopped vehicles on the ramp could be extended upstream of the merge area and used to inhibit the propagation of green bands into ramp vehicles which are stopped anywhere along the ramp.

3. Bands on the display generated only in response to ramp vehicle demand for such bands would save the electrical energy used to illuminate bands when no ramp vehicles are present. The magnitude of the projected power con-

sumption reduction here is not as great as one might expect, however, as a considerable power level is required to keep the high-intensity flashing ballasts and bulbs of the Tampa display element ready to be controlled at the rates used by the control logic.

4. A system design involving the generation of bands only when needed would have the potential for freeing blocks of computer processing time during periods of light ramp demand which could then be used for running other computer programs in a background mode. This is a weak argument when considered in terms of the dedicated mini-computer used to control the Tampa ramp, but could become stronger if one were interested in controlling several ramps with a larger machine.

Improved Strategies for System Mode Control

As reviewed earlier in Chapters 2 and 3, the capability for switching between the various operating modes in response to changing freeway traffic conditions was included in both the Woburn and Tampa Green Band Systems. In both implementations, the freeway state variables of average vehicle velocity upstream of the merge area and combined freeway and merging volume downstream of the merging area were used to operate the mode transition logic (although the Woburn volume logic was disabled, as discussed before).

Observations of the Tampa system public operation have suggested a need for improved mode transition logic to make the ramp control algorithm more responsive to the onset of ramp congestion. For example, in the current control software, ramp congestion per se is not evaluated directly, but, rather, increasing freeway volumes and/or decreasing freeway velocities are used to infer the onset of congestion. When certain threshold values for these parameters are reached, the system is commanded to begin the transition phase to the next appropriate mode. While this strategy performs reasonably well most of the time, vehicle queueing on the ramp can occur without an appropriate control system response to handle it. For example, during moving mode operation, timid drivers waiting in the merge area for relatively large freeway gaps can initiate the formation of a queue of vehicles which extends back up the ramp into the display area. If freeway velocities remain high in such situations, the system remains in moving mode operation, and bands are continually being generated which tend to add vehicles to the queue. Recall that if any of the merge area sensors are occupied for more than five consecutive seconds, the bands are not displayed again until all sensors in the merge area are free, but the system remains in moving mode and the ramp signal rests in green. A more appropriate system response in such cases would be to drop to the stopped-gap metering mode to inhibit queue development in the merge area, thus allowing the accumulated congestion to clear. As no method of detecting queue formation on the ramp is currently implemented, the system is constrained to hold the current mode until freeway conditions change.

A problem related to the one discussed above is the situation where the stopped-gap mode of operation has been active for a period of time and freeway traffic has been heavy enough to cause the formation of a queue of vehicles in the merge area waiting for suitable gaps. (Recall that in SG operation, if the system is unable to find an acceptable gap for a vehicle stopped at the ramp signal, the vehicle is released after a maximum wait at the signal to negotiate a merge without system assistance.) Then, as freeway traffic eases, such as it does at the end of peak periods, the system transitions to the moving mode of operation without regard for any vehicles which may be backed up on the ramp from the merge area. In this instance, the bands can direct moving ramp vehicles into the rear of stopped vehicles, causing potential accident conflicts to develop.

What is needed then, is an on-line method for the detection of ramp queueing (or congestion) which can be used to augment the mode switching logic based on freeway measurements. Several methods for accomplishing this function are available, and could be implemented in the control software without substantially increasing the computing workloads.

Ramp congestion could be detected by monitoring sensor counts throughout the length of the ramp and using these data to determine the number of vehicles stored in each segment of the ramp. Then, if the values for predicted ramp storage exceeded preset thresholds, the system could be commanded to begin the transition from moving mode to stopped-gap operation to clear the congestion. After the congestion had cleared, and assuming the freeway variables allowed it, the system could be directed to re-enter moving mode operation.

Another method for detecting ramp congestion would consist of the computation of the occupancy times for the ramp sensors over some averaging period. Then, as with the other method, a set of threshold values for mode switching could be used to initiate transitions to higher or lower operating modes (e.g., SG to MM or MM to SG).

One factor with respect to the mode control of future merging control systems hardware that should be mentioned is the requirement for a capability for the use of external mode control commands to direct the operations of such systems. As centralized freeway surveillance and control systems gain widespread acceptance and use, it will be necessary to be able to direct the operations of freeway ramps from a remote location, controlling parameters such as metering rates to achieve system performance optimization.

Future Merge Control System Hardware Considerations

As discussed earlier, the primary goal of the Tampa Green Band System Research Project is to determine the feasibility of improving traffic problems associated with merging operations at freeway entrance ramps without reconstruction. Should merge control systems prove to be an effective means of reducing these problems, True and Rosen [87] suggest that future installations of merge control systems will use packaged controller hardware, similar in concept to current systems used for controlling traffic at urban intersections. This section will present a proposed design for such a controller unit, based on a consideration of the essential control functions performed by the current Tampa hardware.

Consider the core map for the Tampa Green Band System Control Program, which appears in Table 8. It is possible to obtain an estimate of program and data storage requirements for future moving merge control hardware by identifying these programs and data storage areas related strictly to the research orientation of the current Tampa system, and then by subtracting the total memory space required for these functions from the 16K (16,384 words) memory used in the Tampa system. As the control programs are written in machine language code, their current sizes may be considered as being representative of lower bounds on the sizes of programs written to do the same job in a higher level language, such as FORTRAN.

A significant block of memory space in the Tampa system is used for data logging purposes. There is no need for an equivalent data logging function in a stand-alone merging control system of the future, since the system design will have been configured and evaluated in research projects as the one described in this thesis. Elimination of the DATA LOGGER routine and the two magnetic tape data buffers from the system core map shown in Table 8 would allow a total reduction of 3,375 (decimal) words of memory space.

Next, there is no need for a situation display board such as the one used in the Woburn and Tampa research

Table 8
Tampa Green Band System
Control Program Core Map

PROGRAM NAME	START ADDRESS	END ADDRESS	LENGTH (DECIMAL WORD COUNT)
	(HEXADECIMAL	VALUES)	
EXECUTIVE/INPUT SERVICE	0	3B6	951
free area	3B7	48F	217
MULTIPLY-DIVIDE	490	53C	173
free area	53D	5BF	131
OPERATOR MONITOR	5C0	7F9	570
free area	7FA	7FF	6
GREEN BAND UPDATE	800	ADD	734
free area	ADE	AFF	34
SENSOR CHECKOUT	B00	B12	19
free area	B13	B7F	109
HIGHWAY VEHICLE PROCESSOR	B80	FD0	1105
free area	FD1	FFF	47
SITUATION DISPLAY	1000	15C8	1481
free area	15C9	15FF	55
DATA LOGGER	1600	1776	375
free area	1777	17FF	137
GREEN BAND STATUS	1800	1F39	1850
free area	1F3A	1FFF	198
VELOCITY-VOLUME	2000	236B	876
free area	236C	23FF	148
TABLE COPY	2400	24A6	167
free area	24A7	27FF	857
FAULT MONITOR	2800	2ACC	717
free area	2ACD	332F	2147
DATA LOGGER MAG TAPE BUFFER 0	3330	390B	1500
DATA LOGGER MAG TAPE BUFFER 1	390C	3EE7	1500
free area	3EE8	3EFF	24
LOAD AND DUMP	3F00	3FF2	243
free area	3FF3	3FFF	13
TOTAL CORE			16,384

projects in a future merge control system, as this board primarily represents a demonstration and analysis tool for the study of the current system implementation. The elimination of the situation display board control program would have the effect of freeing 1,481 words of memory space requirements. Also, in an operational merge control system not involving a research application, there is no need for an operator change and inspect subroutine (OCIS) to permit operator communications with the system, as what will probbly be used to implement system parameter changes in the future will be something on the order of a programmable memory element which could be updated at a central shop location and taken to the field and installed in the merge control system hardware simply by pulling out the existing memory unit and plugging in the new one. The elimination of OCIS would save 570 words.

The use of a programmable read-only memory (PROM) for program storage in future systems would mean that the control program would not have to be re-entered into the system prior to each day's operations or after a power failure. The use of this feature would save at least 243 words of core in the Tampa system (note the LOAD AND DUMP program for processing paper tape input and output in Table 8).

Recall the earlier discussion of the processing functions of the VELOCITY-VOLUME subroutine in the Green Band Control Program (not modified in its basic design philosophy for Tampa) used a table of 600 words of core memory to store freeway vehicle velocity and sensor report timing data. Then, on each entry to the routine, this table was scanned to prepare a velocity average for the last three minutes of vehicle data. Consider an alternate velocity averaging scheme using exponential smoothing over a number of vehicles of the form:

$$\mathrm{VBAR}_{k+1} = (\alpha)(\mathrm{VNEW}) + (1-\alpha)(\mathrm{VBAR}_k),$$

where VBAR_{k+1} = new value for average freeway velocity,

VBAR_k = old value for average freeway velocity,

VNEW = new individual vehicle velocity measurement

α = smoothing parameter, $(0 \leq \alpha \leq 1)$.

It would be possible to eliminate the 600-word data table using this approach, as all past data values are essentially represented in the value of VBAR_k, and the size of the control program could therefore be reduced by a corresponding amount.

Other routines and free storage areas could be eliminated in future systems to save additional space. For example, there is a free core area of 2,147 words between the FAULT MONITOR program and the magnetic tape data buffers which could be eliminated. In addition, if the control computer used in the future merge system design has hardware multiply and divide instructions, the MULTIPLY-DIVIDE program to implement these functions in software could be dropped, saving another 173 words.

The accurate prediction of memory space requirements for programs written for the Raytheon 704 computer is complicated to some extent by the hardware addressing scheme used in the machine. The memory is organized into "pages," each of which is 2,048 decimal words long, and for efficient operation, most program data referencing should be done within a given word page to avoid the need for extra program steps used strictly for addressing data outside the current page. The net effect of this machine architecture is to make it almost mandatory to start long programs, such as GBS, on a word page boundary. The implications of this requirement to the analysis of minimum core space for a merge control system in this section is that not all of the core map in Table 8 marked as free areas can be eliminated, as some wasted space between the end of the programs and the beginning of the next usable word page or byte page boundary is required due to the considerations discussed above.

Consideration, however, of the projected core savings outlined above as being achievable through non-essential program elimination and program data tailoring leads to the conclusion that 8K (8,192 words) memory would be sufficient to operate a green band control system at an isolated ramp location. Some 6K words of this total requirement would be used for program and constant storage, which could be in PROM, and 2K words of random access read-write memory (RAM) would be needed for the storage of variable values which change as the system operates.

Given these memory requirements, Figure 72 represents a schematic diagram of a stand-alone moving merge controller using micro-computer technology as the central control element [97-107]. The system outlined would have a capability equivalent to that represented by the current Tampa system, if the research-oriented facilities were eliminated, as discussed above. Note that only two 16-bit words would be used for sensor processing, as the evaluation loops on the ramp and freeway and the sonic detectors in the merge area in the Tampa system would not be needed. Note also that eleven 16-bit words would be used for ramp sign display control assigned as follows:

1. 10 words (160 bits) for green band display bulb control (only 152 bulbs are used for the green band display in Tampa).

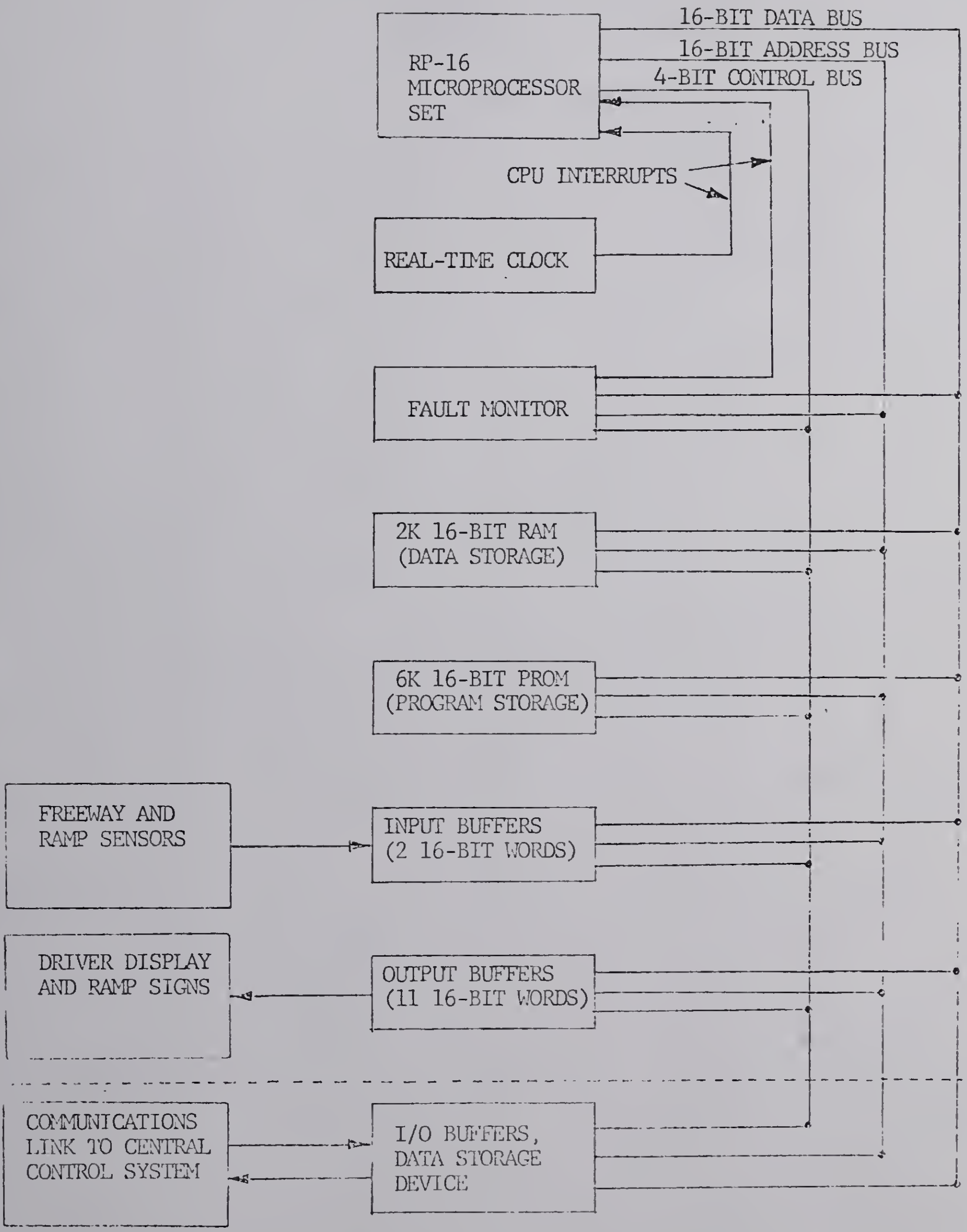

16-BIT DATA BUS
16-BIT ADDRESS BUS
4-BIT CONTROL BUS
RP-16 MICROPROCESSOR SET
CPU INTERRUPTS
REAL-TIME CLOCK
FAULT MONITOR
2K 16-BIT RAM (DATA STORAGE)
6K 16-BIT PROM (PROGRAM STORAGE)
FREEWAY AND RAMP SENSORS
INPUT BUFFERS (2 16-BIT WORDS)
DRIVER DISPLAY AND RAMP SIGNS
OUTPUT BUFFERS (11 16-BIT WORDS)
COMMUNICATIONS LINK TO CENTRAL CONTROL SYSTEM
I/O BUFFERS, DATA STORAGE DEVICE

Figure 72. Schematic Diagram of Moving Merge Controller Using Micro-Computer Technology

2. 1 word (16 bits) of sign control data, as follows:
    a. 1 bit for ramp yield sign control,
    b. 2 bits for the driver advisory sign, coded as:
        00 - sign off
        01 - display "DRIVE BESIDE GREEN BAND"
        10 - display "PREPARE TO STOP"
        11 - spare
    c. 2 bits for the ramp traffic signal, coded as:
        00 - display flashing amber indication
        01 - display red indication
        10 - display solid amber indication
        11 - display green indication

Note that only five bits in the eleventh field control word would actually be needed for controlling the signs used in a Tampa-equivalent system. The remaining bits would be available for other purposes, such as transmitting system status information to a remote location, or possibly signalling a need for maintenance if the built-in fault monitoring circuitry detected a problem with the hardware.

While not included in the cost estimates to be developed later, the hardware shown below the dashed line in Figure 72 could be included in a future merging controller to interface the unit to a centralized freeway surveillance and control system monitoring a network of freeways and ramps. All that would be required to accomplish this function is a set of buffers to hold information to be transmitted to the central unit (or received from the central unit) and a relatively small software routine to initiate a transfer of information in the appropriate direction when activated at fixed time intervals by the ramp controller clock, or when the controller was polled by the master control computer. If the controller was intended for use in a generalized traffic data collection system application, it would be possible to include a small digital cassette tape unit or "floppy-disk" drive in the unit to accumulate traffic data for subsequent transfer to a centralized location during off-peak hours of ramp operation when the computing workloads on the system were lower.

The green band control program simulation model discussed earlier provides an effective tool for establishing performance boundaries on computing hardware requirements for controller functions in future merging control systems. For example, green band flow characteristics on the driver display as a function of calling rates of the GBS and

GBUD routines could be simulated to determine the subroutine timings required in the operational software to achieve specified levels of band quality. Since the processing speed of the computing equipment required to perform these functions is directly related to the frequency with which these routines are called, the use of lower scanning rates would allow slower computing hardware to be used, other factors being equal.

For conservative design, and to insure an adequate processing capability for the proposed controller outlined in this section, however, it was decided to select a computer with a speed and performance approximately equivalent to that of the Raytheon 704 computer used in the Tampa system. Control program timing is an important design constraint, since the Tampa system always enters GBS for full band processing as opposed to the Woburn system feature of doing band processing only when new sensor data was available.

Microcomputers are attractive for use in standalone traffic systems applications primarily because of the low purchase costs associated with these units (less than $100 in quantities of 100 or more). Instruction cycle times of first and second generation microprocessors are typically on the order of 10-20 microseconds, which is adequate for applications such as intersection signal control or simple traffic surveillance. However, the amount of computation associated with freeway vehicle tracking and display control functions made their use in merge control systems infeasible, until the announcement of the third generation of microprocessor technology in 1974. The third generation typically uses BIPOLAR LSI (Large Scale Integration) technology to achieve processing speeds in the 1 microsecond range [98].

One such third-generation microprocessor is the "RP-16 MICROPROCESSOR SET," announced by the Semiconductor Division of the Raytheon Corporation in June, 1974 [106]. This device uses seven LSI integrated circuits of four circuit types to implement the required processing functions for a general-purpose binary computer with a 16-bit word size, a 32-member instruction set, and a basic instruction cycle time of 1 microsecond. Other features of this processor set include the ability to operate from a single five-volt power supply, two-level interrupt logic, eleven program addressing modes, and the ability to meet military standards for operating temperature range performance. Data and control information are transmitted on a 16-bit asynchronous data bus, a 16-bit address bus, and a 4-bit control bus. As relatively complete descriptive information on this unit was available (except for the initial market price), it was used as a representative control computer for the packaged merge controller. Note that the processing speed of the RP-16 is roughly the same as that of the 704, although the 74-member instruction set of the 704 gives it an advantage in programming flexibility.

Two versions of the RP-16 will be produced. Model A has an instruction set oriented to arithmetic-intensive operations, including MULTIPLY and DIVIDE instructions, and can directly address up to 64K words of memory. Model B is oriented to byte handling and thus is useful in communications systems message processing applications. Model A would be used for a merge controller application, primarily due to its hardware multiply and divide capabilities.

Given a basic description of the RP-16 capabilities, then, consider how the merge controller diagrammed in Figure 72 would perform the ramp control function. As in the current Tampa Green Band System, a crystal-controlled oscillator circuit would interrupt the RP-16 at some predetermined system clock rate. The RP-16 would then call an Input Service Routine to acquire the current status of the field sensors and check this information against the values used at the last interrupt to detect sensor events. Tables of completed sensor reports would be passed to a Highway Vehicle Processing Routine to be translated in freeway data tables, and the Green Band Status and Green Band Update routines would function in exactly the same manner as their current counterparts to generate bands and propagate them along the ramp display.

Note the absence of data paths specifically restricted to input and output operations in Figure 72. As mentioned earlier, all information passed to and from the RP-16 card is transmitted on a single 16-bit data bus. Thus, the sensor input buffers and ramp display output buffers would look like memory locations to the RP-16, and data transfer would be accomplished simply by loading the appropriate address of the source or destination of a 16-bit word on the address bus, and then sending a read or write command along the control bus to initiate the transfer operation. Since all of the components of the controller are connected to the various buses at all times, address decoding logic is used to select which unit is to be currently active.

As the controller unit is designed for unattended field operation, the fault monitoring circuitry is of particular importance. Program timing can be monitored in much the same fashion as is done in the current system by resetting a timing circuit at each clock interrupt and halting the system operations if the timer should ever reach a zero condition as a consequence of not being reset within a given time period. Similarly, sensor performance could be monitored by checking vehicle counts at each sensor station against those reported at its neighbors, and shutting down system operation if error tolerances were exceeded.

Power fail-safe capabilities would need to be implemented in the external controller circuitry, as the RP-16 does not have this option. A simple voltage level test could be used to signal the CPU when the power had dropped below unacceptable levels, and an orderly shut-down sequence could be initiated. Then, when power was restored, the initialization mode could be entered to resume normal system operation.

Again, to meet the requirements of unattended field operation for the controller, some means of turning the ramp control system on and off each day would be needed, assuming 24-hour operation was not required. Several options are available for doing this function, including the use of conventional traffic signal timing mechanisms used to change signal patterns for peak and off-peak conditions, which could easily be adapted to the application. Similarly, 24-hour clock timing circuits are available on integrated circuit chips, and could be used in conjunction with prestored system operating time data values in PROM memory to regulate system operations electronically.

The relatively low power consumption of the solid-state logic in the controller unit would allow the use of a storage battery in the cabinet to maintain data storage in the RAM during short periods of power interruption. The provision of a battery would also allow the timing circuitry to be kept running during these periods to avoid the need for maintenance attention after each power failure to reset the time-of-day clocks to the appropriate value. Automatic circuitry could be provided to keep the battery at a fully-charged condition when power was available.

Figure 73 shows the projected configuration of the stand-alone ramp controller. A cabinet five feet high, three feet wide, and two feet deep could easily house the required equipment. Some means of cooling the electronic circuitry would probably be required, but advances in semi-conductor technology over the next few years may drop this requirement to the simple provision of blowers in the cabinet to maintain air circulation (temperatures in the field detector cabinets in Tampa have been recorded in excess of 140°F on sunny days with the cooling fans in operation). At present, however, a 5,000-BTU air conditioner unit would be an inexpensive and effective choice for a cooling unit for the controller housing.

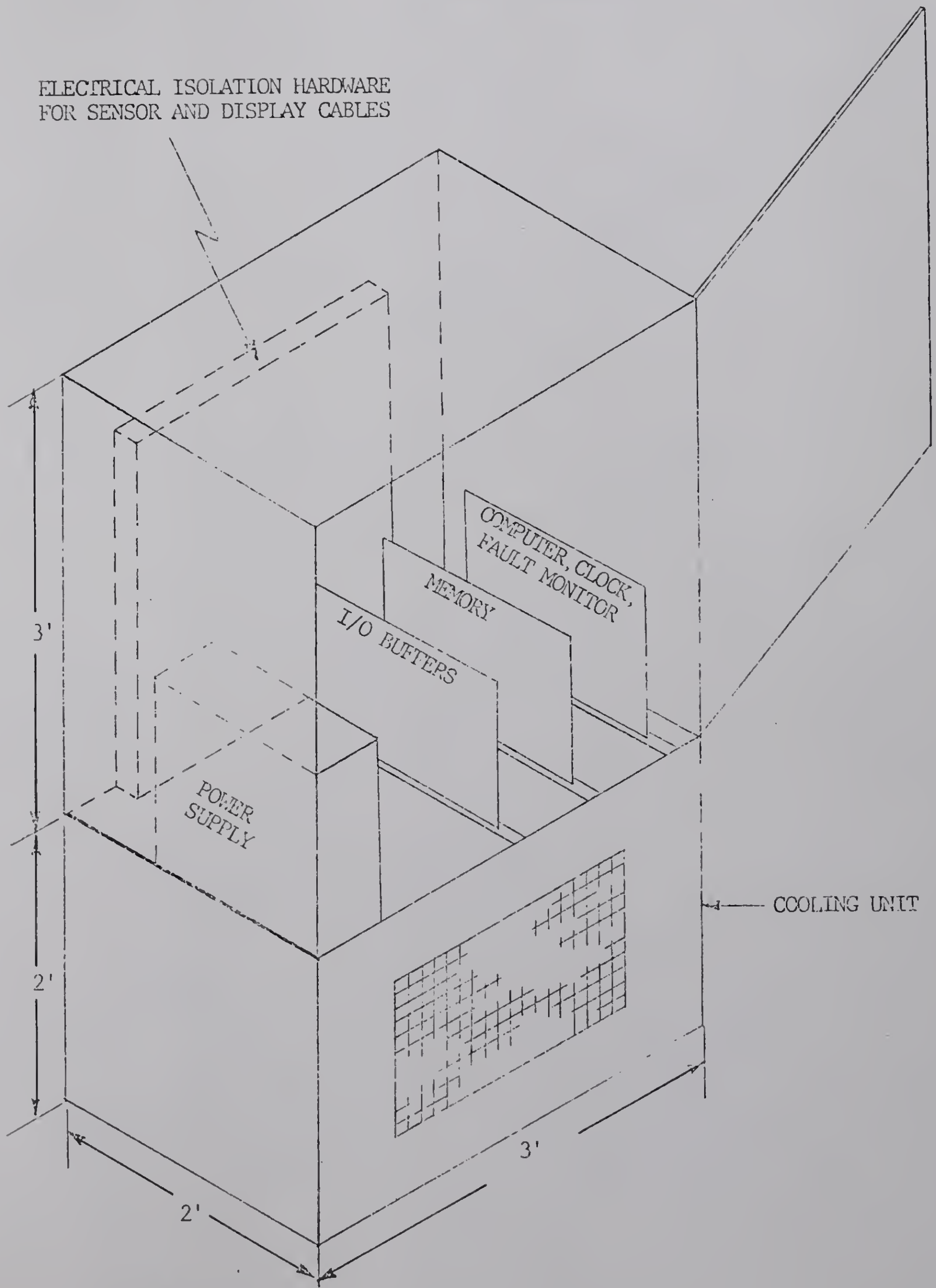

ELECTRICAL ISOLATION HARDWARE
FOR SENSOR AND DISPLAY CABLES
COMPUTER, CLOCK, FAULT MONITOR
MEMORY
I/O BUFFERS
POWER SUPPLY
COOLING UNIT
3'
2'
2'
3'

Figure 73. Projected Configuration of Packaged Moving Merge Controller

Electronic circuitry would be housed on printed circuit boards with edge-mounted connectors for insertion into a card rack running along the bottom of the cabinet. Test points would be provided into the signal paths between the cards to facilitate servicing operations.

Electrical isolation hardware would be provided on a panel at the back of the cabinet, perhaps accessible through a rear door. This hardware would include lightning arrester units [95] on each of the incoming sensor cable lines and on each of the outgoing display control lines.

Table 9 presents an estimated cost breakdown for the packaged moving merge system control. This information was projected from current integrated circuit pricing information and represents early 1975 prices for all components. As noted in the table, Raytheon's Semiconductor Division has not yet released pricing information for the RP-16 microprocessor set, and the indicated cost shown is a conservative estimate, based on released prices of similar products [99]. Also, the engineering and manufacturing overhead allowance of twice raw component cost is only an estimate, but is in line with general electronic industry guidelines for such hardware.

A generalized cost comparison between the current green band system control equipment and the projected con-

Table 9
Estimated Cost Breakdown for
Packaged Moving Merge System Controller (1)

ITEM	COST (DOLLARS)
CPU CARD	$ 1,000 (2)
REAL TIME CLOCK	100
FAULT MONITOR	200
2K RAM MEMORY	750
6K PROM MEMORY	1,000
INPUT BUFFERS	200
OUTPUT BUFFERS	500
POWER SUPPLY	300
CARD RACK	200
ELECTRICAL ISOLATION CIRCUITRY	750
COOLING UNIT	200
CABINET	750
TOTAL COMPONENT COST:	$ 5,950
ENGINEERING AND MANUFACTURING ALLOWANCE (AT TWICE COMPONENT COST):	$11,900
TOTAL PROJECTED COST:	$17,850

Notes:

(1) Does not include interface equipment for use in a freeway surveillance and control system application.

(2) Price data is not yet available for the RP-16 from Raytheon. This is a conservative estimate based on the current prices of comparable units.

troller is possible, but it should be noted that the current system hardware represents the evolution of a prototype engineering test system into an operating ramp control system, and no specific attempt was made to achieve a minimum cost system design in either of the two research implementations tested to date in Woburn and Tampa.

The Raytheon 704 computer has a base price of $7,200 with 4K words of 16-bit memory [91]. Extra memory is available in blocks of 4K words at a cost of $2,000 each, making the total base price of an 8K machine $9,200. Other elements of the current Tampa hardware represented in the controller design include the Input/Output interface unit (which also contains the system clock circuitry), and the Storage Control Unit (which also supports the fault monitor hardware). A conservative estimate of the acquisition cost of this equipment is $10,000, based on available records. Note also that the proposed ramp controller design requires no external peripheral hardware such as that required to communicate with the 704, yielding an additional cost savings of up to several thousand dollars, depending on the equipment selected for this purpose. A teletype ($1,000) could be used for program loading, but the relatively slow input speed of ten frames/second associated with the teletype paper tape equipment makes the use of a high-speed paper tape reader ($2,800 [91]) almost mandatory for this application.

Additional costs are associated with the use of the microcomputer-based ramp merge control system hardware in the current application. For example, the cabinets housing the computer and related equipment cost $950 each, the interrupt system (eight levels) represents an additional cost of $400, and the power fail-safe option costs $750.

Assuming one equipment cabinet and the use of a teletype for system communication, the total "minimum Tampa ramp controller" cost is $22,300, which is $4,450 higher than the projected selling price of the controller design using microprocessor technology. As microprocessor and associated semiconductor technologies continue to develop, the cost differential between design concepts for merge controllers using minicomputers and those using microprocessors will sharply increase. Should the use of merging control systems become widespread, it is possible to envision the development of a "ramp controller set," consisting of integrated circuit chips, which would perform all of the required processing functions, and need only to be connected to sensor and display control lines and supplied with power to operate a ramp.

CHAPTER 6
SUMMARY AND CONCLUSIONS

Summary of Chapter Coverage

Chapter 1 reviewed previous research work in merge control systems and in the traffic flow theory supporting such systems, and discussed the various categories of ramp control measures that have been proposed to date. It was noted that the green band system concept is representative of the more advanced forms of ramp control technology, as it represents an attempt to provide driver assistance throughout the majority of the merging maneuver. Earlier design concepts simply regulated vehicle movements on the ramp using standard traffic signals and left the merging vehicles to complete the merging process without further system direction.

Chapter 2 discussed two prototype moving-merge control systems developed and tested by the Raytheon Corporation in Woburn, Massachusetts, on a ramp with good geometric design characteristics and no associated traffic operational problems in handling the presented merging volumes. A general driver preference was noted for the second system concept tested, which displayed moving bands of light along the ramp corresponding to acceptable gaps in the freeway traffic stream available for merging vehicles. The operating hardware and software for this concept, known as the Woburn Green Band System, was reviewed, and factors relating to the decision to install and evaluate a green-band system at a ramp with a known merging problem were discussed. The site selected for this follow-on work was the Ashley Street entrance ramp to I-75 in downtown Tampa, Florida, and contractual responsibilities of the University of Florida relating to this work were presented.

Chapter 3 reviewed the hardware and software changes from the Woburn system design used to install the Tampa Green Band System. Substantive changes were made in the control algorithms used to operate the earlier system, including the provision for variable-speed green band progression on the field display to accommodate safe vehicle speed levels constrained by the geometric design of the Tampa ramp. In addition, improved logic for system response to merge area congestion was found to be necessary, and was implemented to provide additional safety margins in the public operation of the system.

The Woburn mode change logic was found not to be sufficiently responsive to the requirements of the Tampa site, and logic used to evaluate both freeway vehicle velocities and combined ramp freeway volumes in the mode decision logic in the on-line control program was discussed. System features implemented to reflect the research orientation of the system were described, including a new display mode for the situation display board used in the Woburn system, and improved capabilities for monitoring system activity in real-time through the teletype unit associated with the system.

Chapter 4 reviewed the evaluation plan developed for the Tampa Green Band System. Considerations relating to the need for improved data-logging techniques in the on-line control program were discussed, and the design of new control program software to meet these requirements was presented.

Techniques for the analysis of sensor and system performance data tapes generated on-line by the control program were also discussed in Chapter 4. These techniques were integrated into a software system for automated merge control system performance analysis, and the operations of the various routines in this code were discussed. Examples of reduced data from public operation of the system were presented, and discussed with respect to their application in the overall evaluation scheme.

Chapter 5 reviewed design considerations for future merge control system implementations, based on operating experience gained with the public operation of the Tampa system to date. Problems involving band generation and stability on the field display were identified, and factors in the control software design associated with these conditions were discussed.

Detector hardware characteristics relating to the band stability problem were reviewed, and the development of a technique for the on-line calibration of electrical length parameters of freeway sensor stations to reduce such conditions was presented.

A simulation model developed to facilitate the operational analysis of the on-line green band control program was discussed, and outputs from the model representing system processing of input data obtained from field measurements on actual freeway vehicles in the Tampa system were presented. Design implications of computed band placements on the ramp display representing deviations from desired band activity were reviewed.

Finally, an analysis of the basic processing functions of the Tampa Green Band System in a non-research implementation was used to establish a proposed hardware design for a packaged moving merge system controller using micro-computer technology. Production costs for the new design were projected, and its potential for integration into area-wide freeway surveillance and control systems of the future was discussed.

Conclusions

The green band moving merge control system concept originally developed by the Raytheon Corporation and first tested in Woburn, Massachusetts, has been successfully adapted for use in controlling merging operations at the Ashley Street entrance ramp to I-75 in Tampa, Florida. Although a complete quantitative performance evaluation of traffic operations at the ramp before and after the installation of the control system is beyond the scope of this dissertation, this section will present the research findings that have been determined by observation of the Tampa system performance in public operation, based on the work discussed in Chpaters 3, 4, and 5.

An unrestricted view of the ramp approach, ramp display area, acceleration lane, and upstream freeway area is available from the roof of the control center building housing the green band system control equipment. Thus, it is possible to manually track individual vehicles throughout the ramp area, and to correlate their trajectories against freeway gaps. Using this approach, it is possible to establish that the control system does in fact generate green bands in both the stopped-gap and moving modes of operation which, if followed, lead ramp vehicle drivers into adequate freeway gaps at the designated merge point location, as confirmed by system acceptance tests conducted before public operation began.

Observations of ramp vehicles made before the control system was in operation indicated that a majority of the drivers had to reduce their speed in the initial section of the ramp to maintain adequate vehicle control, as evidenced by the application of braking at the entrance to the curved section (determined by monitoring vehicle brake lights in this area). With the control system in operation, however, a substantial reduction in this condition was observed for those vehicles which were following the displayed green bands. Thus, the variable-speed green band propagation algorithm used in the Tampa system control program appears to be a viable technique for limiting vehicle speeds in the initial section of the ramp, where the radius of curvature allows a maximum safe speed of 30 miles/hour.

In future merging control systems, strong considerations should be given to the use of a limited form of closed-loop control of display activity in both stopped-gap acceptance and moving modes of operation. Full adaptive control of band movements in response to changes in ramp vehicle trajectories (e.g., the Pacer system design concept) is not needed for safe and effective merging control operations, but the condition frequently noted in the operation of the Tampa system of bands moving through stopped or slow-moving vehicles on the ramp represents a potential limitation to the full public acceptance of, and confidence in the use of merge control systems. Masking logic was developed for the Tampa system green bands to eliminate this problem with respect to merge area congestion, but techniques for monitoring ramp vehicle activity along the entire length of the ramp display should be included in the on-line control programs for future systems to allow the detection of potentially hazardous conditions on the ramp.

The Tampa Green Band System modal response to traffic conditions on the freeway was reviewed in Chapter 5, leading to the conclusion that ramp congestion measurements should be used to augment the mode decision logic in the on-line control program. Several approaches for accomplishing this function were suggested, including the use of additional ramp sensors over the number currently processed in the control algorithms to provide a capability for the real-time detection of queue formation on the ramp. Although the use of additional sensors would increase implementation costs, the potential increases in system safety margins and merging capacity achievable with this approach make its use attractive.

Stability of the ramp display information has been a continuing problem with the Tampa system operation. Bands are frequently observed to jump back and forth on the display, and to appear and disappear in segments, rather than moving smoothly along the ramp. The simulation model for the green band control system discussed in Chapter 5 duplicated this behavior, allowing an explanation of the underlying causes of this problem. Possible methods of reducing this undesirable band activity were reviewed, including the use of additional sensor stations in the freeway area, and the implementation of some form of freeway vehicle tracking by the on-line control program, each approach representing additional computing requirements over those of the current system implementation.

The future of moving merge ramp control systems appears bright, as evidenced by the demonstrated capability of the Tampa Green Band System to aid drivers who follow the displayed information.

CHAPTER 7
AREAS FOR FUTURE RESEARCH

Several areas for future research involving moving merge control systems have been suggested by operational experience with the Tampa Green Band System and by the research activities described in this dissertation. Perhaps the most significant of these is the question of the determination of the optimum sensor configurations and related sensor performance measures under expected field operating conditions for merging control systems.

As discussed in Chapter 3, considerable difficulty has been experienced with the inductive loop detectors in the Tampa system as a result of the heavy electrical storm activity in the Tampa Bay area, and all of the detector stations have required frequent adjustment to keep the system in operation. Also, detector fidelity in accurately reporting freeway vehicle characteristics has been something of a problem, as was discussed in Chapter 5. Consideration of freeway and ramp sensor hardware for future merge control systems based on physical principles other than a change of inductance of a loop of wire buried in the road surface is a promising approach to reducing such problems.

For example, Figure 74 shows a photograph taken from a display console screen of the surveillance radar system at Tampa International Airport. The image along the 8-o'clock position vector on the screen represents vehicle movements on the Howard Frankland Bridge segment of I-75 across Tampa Bay. The moving target indication mode of the radar system was activated, reducing the background clutter on the screen from stationary objects, and the movements of vehicle platoons across this section of highway were clearly discernable. It is interesting to note that Raytheon had originally suggested the possibility of using a radar detection system in the Woburn work, but hardware problems prohibited the use of this approach at the time, according to a personal communication with J. A. Wattleworth. Modern electronic technology is developing to the point where the use of less expensive radar systems may well become feasible in future merge control systems, thus eliminating the need for discrete sensors along the ramp and freeway area associated with the controlled ramp. This would eliminate much of the communications hardware costs associated with a merge control application, since the radar unit and a packaged ramp control system such as the one described in Chapter 5 could be co-located at a point near the ramp display elements. Radar surveillance would also allow the capability for semi-continuous vehicle tracking to be implemented in the merge control algorithms,

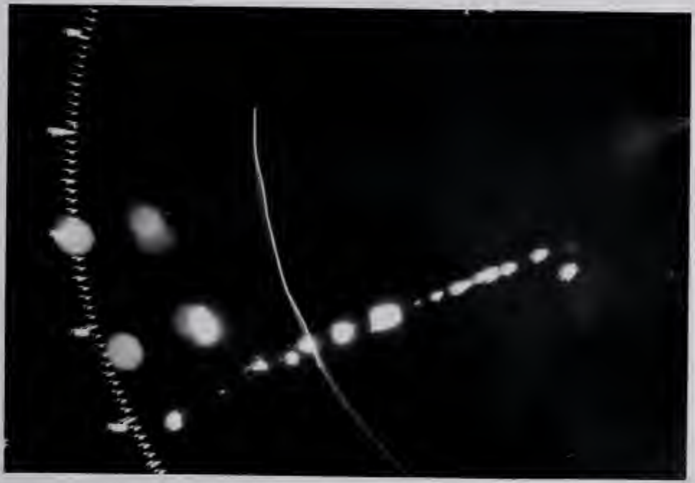


Figure 74. Photograph Taken from the Screen of a Surveillance Radar at Tampa International Airport Showing Freeway Vehicle Traffic on I-75 Across Tampa Bay

as new information on all vehicles in the controlled area would be available at each revolution of the antenna, and band quality in a green band type system could be improved considerably using this approach, as was discussed in Chapter 5.

Given the use of discrete sensor technology, however, the process of freeway vehicle trajectory estimation needs considerable refinement to allow smooth display operations in traffic-responsive control systems such as the green band concept. It was demonstrated in Chapter 5 that band perturbations on the display were caused by positional updates for freeway vehicles which in most cases could have been avoided if the characteristics associated with a given vehicle's arrival at the next downstream station could have been predicted more accurately based on measurements taken at the upstream station. Results from car-following theory can perhaps be applied here to establish projected characteristics for freeway vehicles as they pass thorugh the various sensor stations in a merge control system. Then, each vehicle arrival at a sensor station could be correlated against the predictions made at the upstream station, and if the measured conditions fell within pre-established control limits of the predicted values, no changes would be transmited to the ramp display other than the normal band progression updates. Thus, a smoother and more consistent operation of the ramp display would be achievable.

As with any area of engineering practice, cost and performance trade-offs will be necessary to establish the design criteria for the next generation of merge control systems. For example, the capability for vehicle tracking and classification in real-time in the manner described above will necessitate additional computational power over that needed by the current implementation, and the expected benefits of the new control scheme will have to be balanced against the possible cost increase for the additional or improved system hardware required by the advanced techniques.

With the continuing evolution of micro-computer processing techniology, it will be possible to consider the use of several dedicated computing elements in a single ramp controller, each serving a single processing function such as sensor processing, vehicle tracking, or display control. The projected cost of future micro-processors is low enough to make the multiple-processor approach competitive with systems using a single larger computer to perform the same functions, and computer scientists are already developing analytical design trade-off techniques for such applications [108]. Thus, the packaged controller design discussed in

Chapter 5 may be implemented with several micro-processor units in place of the single processing unit specified to achieve a higher level of computing performance without significant cost increases.

Finally, a detailed human-factors evaluation of the "best" display element configuration for use in moving merge control systems is recommended. Considerable work has been done in such areas as the determination of pilot tracking error for various display system configurations in aerospace engineering applications, but little experimental work has been performed in measuring the operational effectiveness of the various display concepts that have been proposed for moving merge systems for use by the general driving public. A possible direction of research activity here would be to utilize a physical driving simulator to assess driver/display interactions without incurring the costs associated with constructing full-scale displays and testing them in the field. Control system simulation techniques such as those discussed in Chapter 5 would be used to operate the test displays, and much of the system evaluation could be accomplished with an on-line, real-time implementation of the techniques described in Chapter 4.

APPENDIX A

FORTRAN LISTING OF THE TOGAP DATA ANALYSIS ROUTINES

```
//*
//* THE FOLLOWING STATEMENTS ARE THE IBM OS/370 JOB CONTROL
//* LANGUAGE COMMANDS REQUIRED FOR THE EXECUTION OF TOGAP
//* FROM A PROGRAM LIBRARY DATA SET STORED ON A DISK FILE.
//*
//B EXEC PGM=TOGAPX
//STEPLIB DD DSN=PLANPAC,DISP=SHR
//FT06F001 DD SYSOUT=A
//FT07F001 DD SYSOUT=B
//FT08F001 DD SYSOUT=A,DCB=(RECFM=FA,LRECL=133,BLKSIZE=133)
//FT09F001 DD UNIT=(TAPE9,,DEFER),VOL=SER=TOGM31,DISP=(OLD,KEEP),
//  LABEL=(1,NL,,IN),
//  DSN=TRAFFIC.DATA,DCB=(RECFM=U,LRECL=3000,BLKSIZE=3000,DEN=2,
//  EROPT=ACC,BUFNO=1,NCP=1)
//FT10F001 DD SYSOUT=A,DCB=(RECFM=FA,LRECL=133,BLKSIZE=133)
//FT11F001 DD SYSOUT=A,DCB=(RECFM=FA,LRECL=133,BLKSIZE=133)
//FT12F001 DD SYSOUT=A,DCB=(RECFM=FA,LRECL=133,BLKSIZE=133)
//FT16F001 DD SYSOUT=A,DCB=(RECFM=FA,LRECL=133,BLKSIZE=133)
//FT17F001 DD SYSOUT=A,DCB=(RECFM=FA,LRECL=133,BLKSIZE=133)
//FT19F001 DD SYSOUT=A,DCB=(RECFM=FA,LRECL=133,BLKSIZE=133)
//FT20F001 DD UNIT=SYSDA,DCB=(RECFM=VS,BLKSIZE=400),
// SPACE=(CYL,(1,1))
//FT21F001 DD SYSOUT=A,DCB=(RECFM=FA,LRECL=133,BLKSIZE=133)
//FT22F001 DD SYSOUT=B,DCB=(RECFM=F,BLKSIZE=80)
//FT23F001 DD SYSOUT=B,DCB=(RECFM=F,BLKSIZE=80)
//FT05F001 DD *
TEST 1     AFTER PROCESSING WITH FULL OUTPUT (NO PUNCH)  TOGM31/1
01C000011001    900.    080974      0700    0    0    0    1
/*
```

```
C     TAMPA OPERATIONAL GREENBAND ANALYSIS PROGRAM (TOGAP)
C
C     ROUTINE MAIN READS RUN DESCRIPTION CARDS, PRINTS AND PUNCHES
C     OUTPUT HEADINGS, AND CALLS TIMID TO PROCESS EACH CASE.
C
C     INPUT DATA CARDS FOR TOGAP
C            COLS   VARIABLE  OPTION CONTROLLED
C     CARD 1 1-72   HEADER    RUN ID (TAPE NAME, TAPE FILE, DATA, TIME)
C     CARD 2 1      IPLOT     INHIBIT ANALYSIS (DO TAPE SCAN ONLY)
C            2      IHIST     PRINT HISTOGRAMS
C            3      IPRT1     PRINT FREEWAY VEHICLE TRACKS
C            4      IPRT4     PRINT RAMP VEHICLE TRACKS
C            5      INOISE    PRINT ACCELERATION NOISE
C            6      IXX(1)    PRINT GB DRIVER DISPLAY DATA
C            7      IXX(2)    PRINT MERGE ETA TABLES FROM FMDSAV
C            8      IXX(3)    SKIP PRINTOUT OF CUTINS/CUTOUTS (FREEWAY)
C            9      IXX(4)    SKIP PRINTOUT OF CUTINS/CUTOUTS (RAMP)
C            10     IXX(5)    RUN ANOTHER CASE
C            11     KWRITE    PRINT ETABLES FROM DATA TAPE
C            12     IBAFT     STUDY TYPE (0=BEFORE,1=AFTER)
C            13-20  TMAX      STUDY DURATION (SECONDS)
C            25-30  IDATE     DATE OF STUDY (6 DIGITS ... MO/DAY/YR)
C            37-40  MILTYM    TIME OF STUDY (NEAREST 15MIN TIME PERIOD)
C            45     IPUNCH    PUNCH RUN OUTPUTS
C            50     IMRGPN    PUNCH MERGE ANALYSIS DATA
C            55     KGB       PUNCH GB SIMULATION DATA
C            60     KGBPIC    DISPLAY RAMP VEH/GB INTERACTIONS
C
C     LOGICAL I/O UNIT ASSIGNMENTS FOR TOGAP...
C     DEVICE NO.    DEVICE TYPE     USE
C     5             CARD RDR        CONTROL CARD INPUT
C     6             PRINTER         RUN ID, FWY VEH TRACKS, RUN SUMMARY
C     7             CARD PUNCH      STUDY CELL OUTPUT
C     8             PRINTER         FWY ACC NOISE, HISTGMS, SACTON,SCNIC
```

```
C     9             TAPE DRIVE      READ SYSTEM DATA TAPES
C     10            PRINTER         VEH/GB TRACKING DISTANCE
C     11            PRINTER         VEH/GB RELATIVE VELOCITY
C     12            PRINTER         GB WIDTH
C     16            PRINTER         TELETYPE MESSAGES AND ETABLE OUTPUT
C     17            PRINTER         RAMP VEH ACC NOISE
C     19            PRINTER         RAMP VEHICLE TRACKS
C     20            DISK FILE       DRIVER DISPLAY VARIABLES
C     21            PRINTER         MERGE ETA TABLES FROM FMDSAV
C                                   ALSO USED FOR GB GRAPHICS OUTPUT
C     22            CARD PUNCH      MERGE AREA SENSOR HITS
C     23            CARD PUNCH      FWY VEH MERGE ETA'S
C
      COMMON/CALNDR/  IDATE(6),MILTYM,IPUNCH,IMRGPN,TDROP
      COMMON/CIPHER/  S,CI,CO
      COMMON/CONVRT/SNAME(65),NSENHT(65)
      COMMON/GBSHOW/  KGBPIC,TBAND,KGBBMM,KGBBSG ,XNMMB,XNSGB
      COMMON/GBSIM/  KGB
      COMMON/INDI/TIME,LOOP,SENS,CODE,JMAX
      COMMON/PRT/ IPLCT,IHIST,IPRT1,IPRT4,INOISE,IXX(5),TMAX
      COMMON/TITLE/ HEADER(18)
      COMMON/XCNTRL/  KWRITE,IBAFT
      INTEGER SENS,CODE
      INTEGER*2  S(64),CI(64),CO(64)
       REAL*4 KGBBMM(160),KGBBSG(160)
C     INITIALIZE TIME BASE FOR PUNCHED OUTPUT...
      TDROP = 0.
C INITIALIZE MULTIPLE RUN CONTROL VARIABLE...
      LOOP = 0
    9 CALL INIT                                                    INIT
C     CLEAR SENSOR ACTIVITY COUNTERS...
      DO 888 I = 1,65
  888 NSENHT(I) = 0
      READ(5,100) HEADER
      READ(5,101)IPLOT,IHIST,IPRT1,IPRT4,INOISE,IXX,KWRITE,IBAFT,
     *           TMAX,IDATE,MILTYM,IPUNCH,IMRGPN,KGB,KGBPIC
C     ADJUST FOR PRE- JULY 17 REVERSAL OF R6B AND R6A...
      IF(IBAFT.EQ.1)  GO TO 1000
      S(22) = 15
      S(23) = 14
      TNAME = SNAME(22)
      SNAME(22) = SNAME(23)
      SNAME(23) = TNAME
 1000 WRITE(6,1001)
      WRITE(6,80) HEADER,IPLOT,IHIST,IPRT1,IPRT4,INOISE,
     *            IXX,KWRITE,IBAFT,TMAX,IDATE,MILTYM,IPUNCH,IMRGPN,KGB
      WRITE(6,81)  KGBPIC
C     INHIBIT PRINT OF MERGE ETA TABLES IF GBSHOW SELECTED...
      IF(KGBPIC.EQ.1)  IXX(2) = 0
      IF(IPLOT.EQ.1)  GO TO 20
      WRITE(6,1) HEADER
      IF(IPRT1.EQ.1)  WRITE(6,3)
      IF(IBAFT.EQ.0)  GO TO 2000
      IF(IXX(1).EQ.0)  GO TO 2000
      WRITE(10,1)  HEADER
      WRITE(10,105)
      WRITE(10,104)
      WRITE(11,1)  HEADER
      WRITE(11,106)
      WRITE(11,104)
      WRITE(12,1)  HEADER
      WRITE(12,107)
      WRITE(12,104)
 2000 WRITE(16,1)  HEADER
      IF(IPRT4.EQ.1)  WRITE(19,1)  HEADER
      IF(IPRT4.EQ.1)  WRITE(19,200)
      IF(IXX(2).GT.0.OR.KGBPIC.GT.0)  WRITE(21,1)  HEADER
      IF(IPUNCH.EQ.1)  WRITE(7,70)  HEADER
      IF(IMRGPN.EQ.1)  WRITE(22,220)  HEADER
      IF(IMRGPN.EQ.1)  WRITE(23,230)  HEADER
      IF(INCISE.EQ.0) GOTO 20
      WRITE(8,1) HEADER
      WRITE(8,2)
      WRITE(17,1)  HEADER
      WRITE(17,3000)
   20 CALL TIMID                                                        TIMID
      IF(IXX(5).EQ.0)  GO TO 35
C CONTINUATION OF TAPE ANALYSIS REQUIRED...
      LCCP = 1
      GO TO 9
   35 STOP
    1 FORMAT(1H1,18A4,//)
    2 FORMAT(1X,'MEAN ACCELERATION AND ACCELERATION NOISE OF HIGHWAY VEH
     *ICLES WHICH HAVE PASSED F1 '//
     *        '  VEHICLE MEAN NOISE  VEHICLE MEAN NOISE  VEHICLE MEAN NOI
     *SE  VEHICLE MEAN NOISE  VEHICLE MEAN NOISE  VEHICLE MEAN NOISE')
    3 FORMAT(2X,'I  J NE FJ CJ  W ST IN  CAR   DIST    T3       T4
     1 T1       T2       VEL      LEN      ETA     ETA/MP    ACCEL')
   80 FORMAT(///,' INPUT CARDS...',//,1X,18A4,//,
     * 1X,'PARAMETER VALUE ... OPTION CONTROLLED',/,/,
     *  I10,13X,'INHIBIT ANALYSIS PROCESS (DO TAPE SCAN ONLY)',//,
     *  I10,13X,'HISTOGRAM OUTPUT',/,/,
     *  I10,13X,'PRINT FREEWAY VEHICLE TRACKS',/,/,
     *  I10,13X,'PRINT RAMP VEHICLE TRACKS',/,/,
     *  I10,13X,'PRINT ACCELERATION NOISE',/,/,
     *  I10,13X,'PRINT GB DRIVER DISPLAY DATA',/,/,
     *  I10,13X,'PRINT MERGE ETA TABLES FROM FMCSAV',/,/,
     *  I10,13X,'SKIP PRINT OF CUTINS/CUTOUTS (FREEWAY)',//,
     *  I10,13X,'SKIP PRINT OF CUTINS/CUTOUTS (RAMP)',//,
     *  I10,13X,'RUN ANOTHER CASE',/,/,
     *  I10,13X,'EVENT TABLE OUTPUT',/,/,
     *  I10,13X,'BEFORE(0) OR AFTER(1) STUDY',/,/,
   *F10.3,13X,'MAX TIME (SECONDS)',//,
   *2X,2I1,'/',2I1,'/',2I1,13X,'STUDY DATE',//,
   *I10,13X,'STUDY TIME (24 HOUR CLOCK)',//,
   *  I10,13X,'PUNCH RUN OUTPUTS',//,
   *  I10,13X,'PUNCH MERGING ANALYSIS DATA',//,
   *  I10,13X,'PUNCH GB SIMULATION DATA')
 81 FORMAT( /,I10,13X,'DISPLAY RAMP VEH/GB INTERACTIONS')
100 FORMAT(18A4)
101 FORMAT(12I1,F8.0,4X,6I1,6X,I4,4I5)
104 FORMAT( ' VEHICLE     R9      R8      R7     R6B     R6A
   X  R5      R4      R3      R2     MEAN   SIGMA      SUMSQ     MO
   XDE')
105 FORMAT( 1X,'TRACKING DISTANCE OF VEHICLE FROM LEADING EDGE OF GREE
   XN BAND'//)
106 FORMAT( 1X,'RELATIVE VELOCITY BETWEEN VEHICLE AND GREEN BAND'//)
107 FORMAT( 1X,' GREEN BAND WIDTH (FEET)'//)
200 FORMAT(2X,'I  J NE FJ CJ  W ST IN  CAR   DIST    T3      T3(I+1)
   1               VEL',5X,'ACC',/)
1001 FORMAT(1H1,'TAMPA OPERATIONAL GREENBAND ANALYSIS PROGRAM(TCGAP)',
   * //,1X,'VERSION 2.3, NOVEMBER, 1974')
3000 FORMAT(1X,'MEAN ACCELERATION AND ACCELERATION NOISE OF   RAMP  VEH
   *ICLES WHICH HAVE PASSED R1 '//
   *     '  VEHICLE MEAN NOISE  VEHICLE MEAN NOISE  VEHICLE MEAN NOI
   *SE  VEHICLE MEAN NOISE  VEHICLE MEAN NOISE  VEHICLE MEAN NOISE')
 70 FORMAT('CELL    ',18A4)
220 FORMAT('MS HITS ',18A4)
230 FORMAT('FWYETAS ',18A4)
    END
```

```
      BLCCK DATA
C
C     THIS RCUTINE SUPPLIES CCNSTANTS FOR LABELLED COMMONS CIPHER,
C     CONVRT, AND UFHCAT.
C
      COMMCN/CIPHER/  S,CI,CO
      COMMCN/CCNVRT/SNAME(65),NSENHT(65)
      COMMCN/UFHDAT/  UFCELL(64),XNCELL(64),NUFPTR(64)
C
      DATA SNAME/'R9','SPAR','F1-B','F1-A','F2-B','F2-A','F3-B','F3-A',
     1 'F4-B','F4-A','F5-B','F5-A','F6-B','F6-A','F7-B','F7-A','S4',
     2 'S3','S2','S1','R1','R6-B','R6-A','R2','R4','R5','R7','R8',
     3 'SPAR','R12','R10','R11','S11','M8','M7','M6','M1','M5','M4',
     4 'M3','M2','S10','S9','S8','S7','R3','S6','S5','FO-F','FO-C','E2',
     5 'E1','SPAR','FC-A','FO-B','F4-D','F4-C','F4-F','F4-E','F1-E',
     6 'F1-C','FO-E','FO-D','E3','CDSP'/
C
C     CHANNEL NUMBER TC SENSOR COCE...
      INTEGER*2 S(64)  /
     1  11, 0, 7, 7, 6, 6, 5, 5, 4, 4, 3, 3, 2, 2, 1, 1,
     2  32,31,30,29,20,14,15,19,17,16,13,12, 0, 8,10, 9,
     3  39,28,27,26,21,25,24,23,22,38,37,36,35,18,34,33,
     4  49,48,42,41, 0,47,47,43,43,44,44,46,45,49,48,40   /
C
C     CHANNEL NUMBER TO ON-STATUS CODE...
      INTEGER*2 CI(64) /
     1   5, 0, 1, 3, 1, 3, 1, 3, 1, 3, 1, 3, 1, 3, 1, 3,
     2   5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 0, 5, 5, 5,
     3   5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5,
     4   1, 3, 5, 5, 0, 3, 1, 1, 3, 1, 3, 5, 5, 3, 1, 5  /
C
C     CHANNEL NUMBER TC OFF-STATUS CODE...
      INTEGER*2 CO(64) /
     1   6, 0, 2, 4, 2, 4, 2, 4, 2, 4, 2, 4, 2, 4, 2, 4,
     2   6, 6, 6, 6, 6, 6, 6, 6, 6, 6, 6, 6, 0, 6, 6, 6,
     3   6, 6, 6, 6, 6, 6, 6, 6, 6, 6, 6, 6, 6, 6, 6, 6,
     4   2, 4, 6, 6, 0, 4, 2, 2, 4, 2, 4, 6, 6, 4, 2, 6    /
C
C      NCHAN ASSIGNMENTS FOR HISTGM...
C                    NCHAN = 1,11  USED FOR SONICS 1,11
C                    NCHAN = 12    USED FOR TIME IN INIT MODE
C                    NCHAN = 13    USED FOR TIME IN  SM  MODE
C                    NCHAN = 14    USED FOR TIME IN  SG  MODE
C                    NCHAN = 15    USED FOR TIME IN  MM  MODE
C                    NCHAN = 16    USED FOR F7 HEADWAYS
C                    NCHAN = 17    USED FOR F1 HEADWAYS
C                    NCHAN = 19    USED FOR R10/MM HEADWAYS
C                    NCHAN = 20    USED FOR  R1/MM HEADWAYS
C                    NCHAN = 21    USED FOR R10/SM+SG HEADWAYS
C                    NCHAN = 22    USED FOR  R1/SM+SG HEADWAYS
C                    NCHAN = 23    USED FOR RAMP TIME FOR ALL VEHICLES
C                    NCHAN = 26    USED FOR HIGHWAY ACCELERATION NOISE
C                    NCHAN = 27    USED FOR FOA/B HEADWAYS
C                    NCHAN = 28    USED FOR RAMP ACCELERATION NOISE
C                    NCHAN = 33    USED FOR GAP MATCHES AT R1
C                    NCHAN = 41    USED FOR FWY VEH LENGTHS AT F1
C                    NCHAN = 42    USED FOR FWY VEH VELOCITIES AT F1
C
C      HISTOGRAM MAXIMUM DATA VALUES...
       DATA UFCELL    /11*33.0,4*3600.0,7*42.,2*105.,42.,2.1,42.,2.1,
     *                 12*41.,50.,100.,22*10./
C
C      ARRAY TO GIVE MAX NMBR OF CELLS FOR EACH NCHAN ASSIGNMENT
       DATA XNCELL    /11*33.,4*30.,13*21.,12*41.,24*50./
C
C      ARRAY TO GIVE PROPER PRINTER ID FOR HISTGM...
       DATA NUFPTR  / 11*15,53*6/
       END
```

```
      SUBROUTINE ETACHK
C
C     THIS ROUTINE IS CALLED FROM TRACK EACH TIME A NEW FREEWAY
C     VEHICLE ETA AT MERGE POINT IS AVAILABLE.  IF THE CONTROL VARIABLE
C     KGB IS ON , A CARD IS PUNCHED CONTAINING THE DATA PASSED TO THE
C     MASTER CONTROL ROUTINE IN THE ON-LINE GREEN BAND SYSTEM EACH TIME
C     THE HIGHWAY VEHICLE PROCESSOR COMPLETES A FREEWAY VEHICLE STATUS
C     REPORT.
C
      COMMON/GBSIM/  KGB
      COMMON/IND1/TIME,LOOP,SENS,CODE,JMAX
      COMMON/IND3/I,J
      COMMON/TAB/T1(49,7),T2(49,7),T3(49,7),T4(49,7),V(49,7),ETA(49,7),
     1 ETANO(49,7),LEN(49,7),ACC(49,7),CAR(49,7),D(49,7) ,
     2 STAT(49,7),WIRE(49,7)
      COMMON/UFHIST/  IPASS,NCHAN,DELETA
      REAL LEN
      INTEGER CAR,STAT,WIRE,SENS,CODE
      IF(KGB.EQ.0)  RETURN
C     NOTE... THIS OUTPUT IS PUNCHED AHEAD OF STUDY CELL DATA...
      WRITE(7,1000)  I,T2(I,J),CAR(I,J),    V(I,J),LEN(I,J),ETANO(I,J)
 1000 FORMAT('ETACHK...',I1,F12.3,I12,3F12.3)
      RETURN
      END
      SUBROUTINE EVENT
C
C     ON EACH CALL, EVENT DECODES ONE RECORD FROM A DATA TAPE GENERATED
C     BY THE ON-LINE SYSTEM AND PREPARES A TABLE OF SENSOR EVENT
C     ACTIVITIES.  ETABLE ROW ENTRIES ARE CHANNEL NUMBER, ON/OFF STATUS,
C     AND TIME OF THE EVENT.  FIELD DISPLAY EVENTS ARE FLAGGED WITH A
C     CHANNEL NUMBER OF 65 AND STORED IN A DISK FILE FOR USE BY TIMID.
C
      COMMON/CONVRT/SNAME(65),NSENHT(65)
      COMMON/EVENTS/ ETABLE(1000,3),IETROW
      COMMON/NDATA/N,DATA
      COMMON/UFE/KRINHB,KFLAG,CLOCK,KFULL,KFINI,INITI8
       INTEGER*4 IOVFEN,ICLOCK,ICLK1,ICLK2,TBITS,NHIGH,TSTART
      INTEGER*4 KDISC,NHPREV
      INTEGER*4 P /16/
      INTEGER*2 DATA(8,3000)
      INTEGER*2 SDATA(8,8),WORD(16),CODE,BUFFER(8,74)
C
      IF(INITI8.EQ.1)  GO TO 50
      DO 1 I=1,8
      DO 1 J=1,8
    1 SDATA(I,J)=0
      KREP = 0
      KFULL = 0
      KFINI = 0
      NETSIZ = 1000
      CLOCK=0.0
      CRES=.002
      TTYFLG = 0.0
      TFLAG=0.0
      INITI8 = 1
   50 IETROW = 0
      IF(KRINHB.EQ.0)  GO TO 51
      KRINHB = 0
      GO TO 101
   51 CALL TREAD
      KREP = KREP + 1
      IF (KFLAG .EQ. 0) RETURN
      IF(N)  1001,1002,100
 1001 WRITE (P,1000) KREP
 1000 FORMAT(' WARNING...PARITY ERROR ON RECORD NO. ',I4)
      STOP
 1002 KFINI = 1
      RETURN
  100 NWORK=0
      NLFTB=1
      NRTB=2
  101 IF (NWORK .GE. N) RETURN
      DO 105 J=1,8
      WORD(J)=DATA (J,NLFTB)
  105 WORD (J+8)=DATA(J,NRTB)
      CODE = WORD(1)*8+WORD(2)*4+WORD(3)*2+WORD(4)+1
      IF(TTYFLG.EQ.1.)  GO TO 109
      IF(CODE.EQ.9 )  GO TO 106
      IF(CODE.EQ.13) GO TO 107
      NWORK = NWORK + 2
      NLFTB = NLFTB + 2
      NRTB = NRTB + 2
      GO TO 101
  106 TTYFLG = 1.0
      GO TO 250
  107 NWORK = NWORK + 30
      NLFTB = NLFTB + 30
      NRTB = NRTB + 30
      GO TO 101
  109 IF(TFLAG.EQ.1) GO TO 110
      IF(CODE.EQ.13) GO TO 1610
      IF(CODE.EQ.16) GO TO 1616
      NWORK=NWCRK + 2
      NLFTB=NLFTB+2
      NRTB=NRTB+2
      GC TO 101
C     CRIVER DISPLAY EVENT...
 1610 NWORK=NWCRK+30
      NLFTB=NLFTB+30
      NRTB=NRTB+30
      GO TC 101
 1616 TFLAG=1.0
      CC 1617 J=1,8
      WORD(J)=DATA(J,NLFTB)
 1617 WORD(J+8) = CATA(J,NRTB)
      TSTART=0
      CC 1618 K=4,15
 1618 TSTART=TSTART + 2**(K-4)*WORD(20-K)
      TSTART = TSTART*16
      ICLK1=0
      ICLCCK=0
      ICLK2=0
      NHIGH=0
      IOVFEN=0
      CLCCK=0.0
      GO TC 101
C
  110 GCTC(2C0,200,200,200,200,200,200,200,250,201,300,201,350,201,201,
     1400),CODE
  201 WRITE(P,1C05) CCCE
 1005 FORMAT(' WARNING...TAPE CODE VALUE= ',I20)
      STOP
C
C SEGMENT TO PROCESS SENSOR BYTE TAPE DATA...
  200 TBITS = WORD(5)*8+WORD(6)*4+WORD(7)*2+WORD(8)
      ICLCCK=ICLK1+TBITS
      CLOCK=ICLOCK*CRES
      NBASE=(CODE-1)*8
      DO 205 ISCAN=1,8
      NCHAN = NBASE + ISCAN
      IF(SDATA(CODE,ISCAN) - WORD(ISCAN+8)) 210,205,215
  210 CNOFF = 1.
      GO TO 218
  215 CNOFF = 0.
  218 IETROW=IETROW+1
      IF(IETROW.GT.NETSIZ)  GO TO 500
         ETABLE(IETROW,1) = NCHAN
         ETABLE(IETROW,2) = CNOFF
         ETABLE(IETROW,3) = CLOCK
         SDATA(CODE,ISCAN) = WORD(ISCAN+8)
  205 CONTINUE
      NWORK = NWORK+2
      NLFTB = NLFTB+2
      NRTB = NRTB+2
      GOTO 101
C
C SEGMENT TO PROCESS LABEL BLOCK TAPE DATA...
  250 IF((N-NWORK).GE.74)  GO TO 251
      KRINHB = 1
      KAVAIL = N - NWORK
      KCOPY = 0
      DO 2050 ICOPY = NLFTB,N
      KCOPY = KCOPY + 1
      DO 2050 JCOPY = 1,8
 2050 BUFFER(JCOPY,KCOPY) = DATA(JCOPY,ICOPY)
      CALL TREAD                                                        TREAD
      IF(N)  1001,1002,2060
 2060 NNEED = 74 - KAVAIL
      DO 2070 ICOPY = 1,NNEED
      DO 2070 JCOPY = 1,8
 2070 BUFFER(JCOPY,KAVAIL+ICOPY) = DATA(JCOPY,ICOPY)
      NGO = 3
      NSTOP = 74
      CALL XLABEL(BUFFER,CLOCK)                                          XLABEL
      NWORK = NNEED
      NLFTB = NWORK + 1
      NRTB = NWORK + 2
      RETURN
  251 NGO=NLFTB+2
      NSTOP=NGO+71
      NDIFF = NGO - 1
      DO 2071 ICOPY=NGO,NSTOP
      DO 2071 JCOPY = 1,8
 2071 BUFFER(JCOPY,ICOPY-NDIFF) = DATA(JCOPY,ICOPY)
      CALL XLABEL(BUFFER,CLOCK)                                          XLABEL
      NWORK = NWORK+74
      NLFTB = NLFTB+74
      NRTB = NRTB+74
      GOTO 101
C
C SEGMENT TO PROCESS END BLOCK TAPE DATA...
  300 KFINI = 1
      RETURN
C
C     SEGMENT TO PROCESS DRIVER DISPLAY TAPE DATA...
  350 IF((N-NWORK).GE.30)  GO TO 351
      KRINHB = 1
      KAVAIL = N - NWORK
      KCOPY = 0
      DO 3050 ICOPY = NLFTB,N
      KCOPY = KCOPY + 1
      DO 3050 JCOPY = 1,8
 3050 BUFFER(JCOPY,KCOPY) = DATA(JCOPY,ICOPY)
      CALL TREAD
      IF(N)  1001,1002,3060
 3060 NNEED = 30 - KAVAIL
      DO 3070 ICOPY = 1,NNEED
      DO 3070 JCOPY = 1,8
 3070 BUFFER(JCOPY,KAVAIL+ICOPY) = DATA(JCOPY,ICOPY)
      CALL XDDSP(BUFFER,CLOCK,KXSDIS)                                   XDDSP
      NSENHT(65) = NSENHT(65) + 1
      NWORK = NNEED
      NLFTB = NWORK + 1
      NRTB = NWORK + 2
      RETURN
  351 NSTOP = NLFTB + 29
      NDIFF = NLFTB - 1
      DO 3071 KCOPY = NLFTB,NSTOP
      DO 3071 JCOPY = 1,8
 3071 BUFFER(JCOPY,KCOPY-NDIFF) = DATA(JCOPY,KCOPY)
      CALL XDDSP(BUFFER,CLOCK,KXSDIS)                                   XDDSP
      IF(KXSDIS.EQ.1)  GO TO 500
      NSENHT(65) = NSENHT(65) + 1
      NWORK=NWORK+30
      NLFTB = NLFTB + 30
      NRTB = NRTB + 30
      GO TO 101
C
C     SEGMENT TO PROCESS CLOCK OVERFLOW DATA FROM TAPE RECORD...
  400 NFLAG=0
      NHPREV=NHIGH
      NHIGH=0
      DO 405 K=4,15
      NFLAG=NFLAG+WORD(20-K)
  405 NHIGH=NHIGH + WORD(20-K)*2**(K-4)
      NHIGH=NHIGH*16
      IF(NFLAG.EQ.12) GO TO 430
      IF(NHIGH.LE.NHPREV) GO TO 440
      ICLCCK=ICLK2+NHIGH-TSTART
      ICLK1=ICLCCK
      GC TC 450
  430 IOVFEN=1
      ICLCCK=ICLK2+NHIGH-TSTART
      ICLK1=ICLCCK
      GC TC 450
  440 IF(IOVFEN.EQ.1) GO TC 445
      ICLCCK=0
      ICLK1=0
      ICLK2=0
      TSTART=0
      IETRCW=IETROW+1
      IF(IETROW.GT.NETSIZ) GO TO 5C0
      ETABLE(IETROW,1)=999.
      ETABLE(IETROW,2)=0.
      ETABLE(IETROW,3)=0.
      GC TC 450
  445 ICLCCK = ICLK2 + (65536-TSTART)
      ICLK1=ICLOCK
      ICLK2=ICLCCK
      TSTART=0
      IOVFEN=0
  450 CLCCK=ICLOCK*CRES
      NWCRK=NWCRK+2
      NLFTB=NLFTB+2
      NRTB=NRTB+2
      GO TC 101
C
C     ETABLE FULL....ABORT LOGIC
  500 KFULL = 1
      IETROW = IETROW - 1
      WRITE(P,501)  CLCCK
  501 FORMAT(//,' WARNING...ETABLE OVERFLOW AT CLOCK = ',F1C.3)
```

```
RETURN
END
```

```
      SUBROUTINE FGPMR1
C
C     THIS ROUTINE IS CALLED FROM TRACK WHEN A RAMP VEHICLE
C     ENTERS R1.  THE FREEWAY VEHICLE MERGE ETA TABLE IS SEARCHED
C     TO FIND A GAP CORRESPONDING TO THE EXPECTED TIME OF ARRIVAL
C     OF THE RAMP VEHICLE AT THE MERGE POINT.  STATISTICS
C     FOR THIS PROJECTED GAP ARE ACCUMULATED.
C
      COMMON/IND1/TIME,LOOP,SENS,CODE,JMAX
      COMMON/IND3/I,J
      COMMON/TAB/T1(49,7),T2(49,7),T3(49,7),T4(49,7),V(49,7),ETA(49,7),
     1 ETANO(49,7),LEN(49,7),ACC(49,7),CAR(49,7),D(49,7) ,
     2 STAT(49,7),WIRE(49,7)
      COMMON/UFHIST/  IPASS,NCHAN,FGAPR1
      COMMON/XMDATA/ XMETA(60),XMT2(60),XMVEL(60),XMLEN(60),NXM
      REAL LEN
      INTEGER CAR,STAT,WIRE,SENS,CODE
C     AVERAGE TRAVEL TIME FROM F1 TO MERGE POINT...
      DATA TF1MP / 5.0 /
C     ESTIMATE ETA AT MERGE POINT FOR RAMP VEHICLE...
      IF(V(I,J).EQ.0.)  V(I,J) = 44.
      ETAMP = TIME + 284./V(I,J)
C     LOOK IN FREEWAY MERGE ETA TABLE FOR APPROPRIATE GAP...
C     SEARCH FOR TRAILING VEHICLE...
      DO 1 K = 1,NXM
      IF(XMETA(K).GT.ETAMP)  GO TO 2
    1 CONTINUE
C     NO TRAILING VEHICLE FOUND, USE DISTANCE BEHIND LEAD VEH AS GAP...
      IF(ETAMP.LT.XMETA(NXM))  RETURN
C     ( GAP IS AT LEAST THIS BIG, SO INCLUDE NULL SPACE ON FREEWAY)
      FGAPR1 = ETAMP - XMETA(NXM) + TF1MP
      GO TO 3
C     SEE IF TRAILING VEHICLE WAS ONLY TABLE ENTRY...
    2 IF(K.EQ.1)  RETURN
```

```
C     LEADING AND TRAILING VEHICLES FOUND...
      FGAPR1 = XMETA(K) - XMLEN(K) - XMETA(K-1)
    3 NCHAN = 33
      CALL HISTGM                                                       HISTGM
      RETURN
      END
      SUBROUTINE FMDSAV
C
C     THIS ROUTINE IS CALLED EACH TIME A VEHICLE LEAVES F1-B AND
C     SUBROUTINE TRACK COMPUTES A MERGE POINT ETA FOR THE VEHICLE.
C     A TABLE OF FREEWAY VEHICLE MERGE POINT ETA'S IS UPDATED WITH THE
C     NEW INFORMATION, AND THE CURRENT DATA IS PUNCHED FOR GAP STUDIES.
C
      COMMON/CALNDR/  IDATE(6),MILTYM,IPUNCH,IMRGPN,TDROP
      COMMON/EPUNCH/  METCUT(12),LINETA
      COMMON/IND1/TIME,LOOP,SENS,CODE,JMAX
      COMMON/IND3/I,J
      COMMON/PRT/ IPLOT,IHIST,IPRT1,IPRT4,INOISE,IXX(5),TMAX
      COMMON/TAB/T1(49,7),T2(49,7),T3(49,7),T4(49,7),V(49,7),ETA(49,7),
     1 ETANO(49,7),LEN(49,7),ACC(49,7),CAR(49,7),D(49,7) ,
     2 STAT(49,7),WIRE(49,7)
      COMMON/XMDATA/ XMETA(60),XMT2(60),XMVEL(60),XMLEN(60),NXM
      REAL LEN
      INTEGER CAR,STAT,WIRE,SENS,CODE
C     FOLLOWING STATEMENT CONTROLS ETA RETENTION TIME
C     ( E.G., ETA VALUES THIS MUCH OLDER THAN CLOCK TIME WILL BE DROPPED)
      DATA THOLD/20.0/
C     AT ENTRY TO FMDSAV, NXM IS   OF VALID DATA ITEMS IN TABLE...
C     THROW OUT OLD ETA'S...
      DO 1 K = 1,NXM
      IF((TIME-XMETA(K)).GT.THOLD)  XMETA(K) = 1.0E50
    1 CONTINUE
C     PUT NEW DATA IN TABLE...
    2 NXMP1 = NXM + 1
      XMETA(NXMP1) = ETANO(I,J)
      XMT2(NXMP1) = T2(I,J)
      XMVEL(NXMP1) =   V(I,J)
C     NOTE... VEHICLE LENGTH IS STORED IN UNITS OF TIME...
      XMLEN(NXMP1) = 0.0
      IF(V(I,J).GT.0.)  XMLEN(NXMP1) = LEN(I,J)/V(I,J)
```

```
C     PUNCH FWY VEH MERGE ETA DATA, IF REQUESTED...
         IF(IMRGPN.EQ.0)  GO TO 99
         METOUT(LINETA  ) = TIME * 1000.
         METOUT(LINETA+1) = V(I,J)*1000.
         METOUT(LINETA+2) = XMLEN(NXMP1)*1000.
         LINETA = LINETA + 3
         IF(LINETA.LT.12)  GO TO 99
         LINETA = 1
         WRITE(23,5002)  METOUT
C     SORT XMETA VECTOR INTO ASCENDING ORDER
   99 DO 3 K = 1,NXM
      KP1 = K + 1
      DO 3 KSCAN = KP1,NXMP1
      IF(XMETA(K).LE.XMETA(KSCAN))  GO TO 3
      XHOLD = XMETA(K)
      XMETA(K) = XMETA(KSCAN)
      XMETA(KSCAN) = XHOLD
      XHOLD = XMT2(K)
      XMT2(K) = XMT2(KSCAN)
      XMT2(KSCAN) = XHOLD
      XHOLD = XMVEL(K)
      XMVEL(K) = XMVEL(KSCAN)
      XMVEL(KSCAN) = XHOLD
      XHOLD = XMLEN(K)
      XMLEN(K) = XMLEN(KSCAN)
      XMLEN(KSCAN) = XHOLD
    3 CONTINUE
C     ADJUST NXM COUNTER TO REFLECT ONLY VALID ETA TIME VALUES...
      DO 4 K = 1,NXMP1
      IF(XMETA(K) .GT. 1.0E40)  GO TO 5
      NXM = K
    4 CONTINUE
    5 IF(IXX(2).EQ.0)  RETURN
      WRITE(21,100)
      DO 200 K = 1,NXM
  200 WRITE(21,101)  XMETA(K),XMT2(K),XMVEL(K),XMLEN(K)
      RETURN
  100 FORMAT(1X,40('-'))
  101 FORMAT(1X,4F10.3)
 5002 FORMAT(4(3I6))
      END
      SUBROUTINE GRBAND
C
C     GRBAND WILL BE CALLED ONLY WITH INTERNAL SENSOR NUMBERS
C     11 - 19 (MM) AND 15 - 19 (SG), CORRESPONDING TO RAMP SENSORS
C     R9,R8,R7,R6B,R6A,R5,R4,R3,R2.  THIS ROUTINE RECORDS GB TRACKING
C     DISTANCE, GB VELOCITY DIFFERENCE, AND BAND WIDTH (MM ONLY ) FOR EACH
C     RAMP VEHICLE WITH A VALID TRACK.
C
      COMMON/AA2/GO,FLAG,CAR10
      COMMON/GBPROB/  NSGTRY(9),NSGOK(9),NMMTRY(9),NMMOK(9)
      COMMON/EXT2/TTRDM,TTRDS,TTRDC,SSTRM(9),SSTRS(9),SSTRC(9),
     X             TTRVM,TTRVS,TTRVC,SSVM(9),SSVS(9),SSVC(9)
      COMMON/FIELD/DRDISP,DBGB,PTS,RED,AMBER,GREEN,
     1              VMRG,VBAR,C,MWC,MODE,GBMASK
      COMMON/IND1/TIME,LOOP,SENS,CODE,JMAX
      COMMON/IND2/ NE(49),FJ(49),CJ(49),NH,NR
      COMMON/IND3/I,J
      COMMON/PRT/ IPLOT,IHIST,IPRT1,IPRT4,INCISE,IXX(5),TMAX
      COMMON/STAT7/TIN(49),TOUT(49),TCC(49),TNCC(49),PTCC(49)
      COMMON/TAB/T1(49,7),T2(49,7),T3(49,7),T4(49,7),V(49,7),ETA(49,7),
     1 ETANO(49,7),LEN(49,7),ACC(49,7),CAR(49,7),D(49,7) ,
     2 STAT(49,7),WIRE(49,7)
      COMMON/TRBAND/BW(9,120),BWM,BWS,BWC,SBWM(9),SBWS(9),SBWC(9)
      COMMON/TRVD/TRDIST(9,120),TRDM,TRDS,TRDC,STRM(9),STRS(9),STRC(9)
      COMMON/TRVV/TRVEL(9,120),TRVM,TRVS,TRVC,SVM(9),SVS(9),SVC(9)
      COMMON/UFHIST/ IPASS,NCHAN,CT
      REAL LEN
      INTEGER CARX,FJ,CJ,CAR,WIRE,STAT,CAR10
      INTEGER*2  DRDISP(160),DBGB,PTS,RED,AMBER,GREEN,
     1              VMRG,VBAR,C,MWC,MODE,GBMASK
      LOGICAL GO,FLAG
      DATA BIG,DZERO /99999.,443.0/
C     TAMPA RAMP SENSOR LEADING EDGE VS BULB NMBR...
      INTEGER*4  GBBULB(9) / 12,30,49,59,67,86,104,122,140 /
```

```
C     TAMPA SG BAND VELOCITY VS SCALED SENSOR NUMBER...
      REAL*4 SGBVEL(86) / 7*0.0,7.2,10.2,12.0,13.9,15.6,17.0,18.6,19.6,
     *21.0,21.8,23.0,24.0,25.1,26.0,26.8,27.7,28.7,29.4,30.2,30.8,31.4,
     *32.0,32.8,33.4,33.8,34.4,35.0,35.6,36.3,36.8,37.3,37.8,38.4,38.9,
     *39.4,39.9,40.3,40.6,41.0,41.4,41.7,42.0,42.5,42.9,43.2,43.7,44.0,
     *44.4,44.8,45.1,45.5,45.9,46.2,46.5,46.8,47.0,47.3,47.5,47.8,48.1,
     *48.4,48.6,48.7,49.0,49.3,49.5,49.8,50.0,50.2,50.5,50.7,50.9,51.2,
     *51.4,51.6,51.9,52.2,52.4,52.6 /
      IF(CAR10.EQ.0 .OR. CAR(I,J).LT.CAR10) RETURN
      CARX=CAR(I,J)
      IF(CARX.EQ.0)  CARX = 1
      MCAR = CARX - 1
      K = 1 + MOD(MCAR,120)
      IF(CARX.EQ.1)  K = 1
      VMERGE  = VMRG
C     VEHICLE AT SENSOR I, I = 11,19. FIND BAND WIDTH.
      M = I - 10
C     COUNT NUMBER OF VEHICLES CROSSING THIS SENSOR...
      IF(MODE.EQ.2)  NSGTRY(M) = NSGTRY(M) + 1
      IF(MODE.EQ.3)  NMMTRY(M) = NMMTRY(M) + 1
      IPOS = GBBULB(M)
      IUP = IPOS + 2
      IDOWN = IPOS - 2
      DO 10 II = IDOWN,IUP
      IF(DRDISP(II).EQ.1)  GO TO 20
   10 CONTINUE
C     NO BULBS LIT WITHIN PLUS OR MINUS 20 FT OF SENSOR...
      GO TO 400
   20 MARK = II
      DO 30 IEND = II,152
      IF(DRDISP(IEND).EQ.0)  GO TO 40
   30 CONTINUE
      IEND = 152
      GO TO 50
   40 IEND = IEND - 1
   50 MARKM1 = MARK - 1
      DO 60 ILOCK = 1,MARKM1
      ISTART = MARK - ILOCK
      IF(CRDISP(ISTART).EQ.1)  GO TO 60
      ISTART = ISTART + 1
      GO TO 1080
   60 CONTINUE
      ISTART = 1
 1080 CONTINUE
      RMPVEL = V(I,J)
      GBV = SGBVEL(IEND-66)
      IF(MODE.EQ.2)  GO TO 2000
      IF(IEND.LE.66)   GBV = 44.
      IF(IEND.GT.67)   GBV = SQRT(IEND*24+352.)
 2000 GBV = AMIN1(GBV,VMERGE)
      DELTAV = GBV - RMPVEL
      BWIDTH = (IEND-ISTART)*4.
C     COUNT NUMBER OF VALID GREEN BANDS AT THIS SENSOR...
      IF(MODE.EQ.2)  NSGOK(M) = NSGOK(M) + 1
      IF(MODE.EQ.3)  NMMOK(M) = NMMOK(M) + 1
      BW(M,K) = BWIDTH
      TRDIST(M,K) = (IEND-IPOS)*4.
      TRVEL(M,K) = DELTAV
C RECORD BAND WIDTH FOR MEAN AND SIGMA AT THIS SENSOR
   82 TEMP=BW(M,K)
      IF(MODE.EQ.2)  GO TO 85
      SBWM(M)=SBWM(M)+TEMP
      SBWS(M)=SBWS(M)+TEMP*TEMP
      SBWC(M)=SBWC(M)+1.
C RECORD TRACKING DISTANCE FOR MEAN AND SIGMA AT THIS SENSOR
   85 TEMP=TRDIST(M,K)
      IF(MODE.EQ.2)  GO TO 86
      STRM(M)=STRM(M)+TEMP
      STRS(M)=STRS(M)+TEMP*TEMP
      STRC(M)=STRC(M)+1.
      GCTC 87
   86 SSTRM(M)=SSTRM(M)+TEMP
      SSTRS(M)=SSTRS(M)+TEMP*TEMP
      SSTRC(M)=SSTRC(M)+1.
C RECCRD RELATIVE VELCCITY FOR MEAN AND SIGMA AT THIS SENSOR
  87  TEMP=TRVEL(M,K)
      IF(TEMP.EQ.BIG)GCTO 90
      IF(MCDE.EQ.2)  GC TO 88
      SVM(M)=SVM(M)+TEMP
      SVS(M)=SVS(M)+TEMP*TEMP
      SVC(M)=SVC(M)+1.
      GCTC 90
   88 SSVM(M)=SSVM(M)+TEMP
      SSVS(M)=SSVS(M)+TEMP*TEMP
      SSVC(M)=SSVC(M)+1.
   90 IF(I.NE.19) RETLRN
C VEHICLE IS LEAVING SENSCR R2
   91 CO 1C0 II=1,9
      IF(BW(II,K).EQ.C.)TRDIST(II,K)=BIG
      TEMP=TRDIST(II,K)
      IF(TEMP.EQ.BIG)GCTO 100
      TRCM=TRDM+TEMP
      TRDS=TRDS+TEMP*TEMP
      TRDC=TRDC+1.
  100 CCNTINUE
      IF(TRDC.EQ.0.) GCTO 199
      TRDM=TRDM/TRDC
      TRDSQ=SQRT(TRCS/TRDC-TRCM*TRDM)
      IF(IXX(1).EQ.0)  GO TO 102
      IF(MCDE.EQ.2)  GC TO 101
      WRITE(10,31)CARX,(TRDIST(M,K),M=1,9),TRDM,TRDSQ,TRDS
      GOTC 102
```

```
101 WRITE(10,41)CARX,(TRDIST(M,K),M=4,9),TRDM,TRDSQ,TRDS
102 TRDC=0.
    TRDM=0.
    TRDS=0.
    TRDSQ=0.
199 DO 200 II=1,9
    IF(BW(II,K).EQ.0.)TRVEL(II,K)=BIG
    TEMP=TRVEL(II,K)
    IF(TEMP.EQ.BIG)GOTO 200
    TRVM=TRVM+TEMP
    TRVS=TRVS+TEMP*TEMP
    TRVC=TRVC+1.
200 CONTINUE
    IF(TRVC.EQ.0.) GOTO 299
    TRVM=TRVM/TRVC
    TRVSQ=SQRT(TRVS/TRVC-TRVM*TRVM)
    IF(IXX(1).EQ.0)  GO TO 202
    IF(MODE.EQ.2)  GO TO 201
    WRITE(11,31)CARX,(TRVEL(M,K),M=1,9),TRVM,TRVSQ,TRVS
    GOTO 202
201 WRITE(11,41)CARX,(TRVEL(M,K),M=4,9),TRVM,TRVSQ,TRVS
202 TRVM=0.
    TRVC=0.
    TRVS=0.
    TRVSQ=0.
299 DO 300 II=1,9
    IF(BW(II,K).EQ.0.)BW(II,K)=BIG
    TEMP=BW(II,K)
    IF(TEMP.EQ.BIG)GOTO 300
    BWM=BWM+TEMP
    BWS=BWS+TEMP*TEMP
    BWC=BWC+1.
300 CONTINUE
    IF(BWC.EQ.0.)GOTO 399
```

```
      BWM=BWM/BWC
      BWSQ=SQRT(BWS/BWC-BWM*BWM)
      IF(IXX(1).EQ.0)  GO TO 399
      IF(MODE.EQ.2)  GO TO 301
      WRITE(12,31)CARX,(BW(M,K),M=1,9),BWM,BWSQ,BWS
      GOTO 399
  301 WRITE(12,41)CARX,(BW(M,K),M=4,9),BWM,BWSQ,BWS
  399 BWM=0.
      BWS=0.
      BWSQ=0.
      BWC=0.
      DO 401 M=1,9
      TRDIST(M,K)=0.
      TRVEL(M,K)=0.
  401 BW(M,K)=0.
      RETURN
  400 TRVEL(M,K)=BIG
      TRDIST(M,K)=BIG
      BW(M,K)=BIG
      IF(I.EQ.19)GOTO 91
      RETURN
   31 FORMAT(I6,2X,10(3X,F6.2),F7.2,E15.8,'  MM')
   41 FORMAT(I6,29X,7(3X,F6.2),F7.2,E15.8,'  SG')
      END
      SUBROUTINE HISTGM
C
C     HISTGM RECORDS DATA STATISTICS (MEAN,VAR,STD,MIN,MAX,COUNT) AND
C     PRODUCES FREQUENCY HISTOGRAMS AT THE END OF EACH STUDY PERIOD.
C
C     IPASS=1, INITIALIZE COUNTERS
C     IPASS=2, LOAD DATA ON A SPECIFIED CHANNEL...
C     IPASS=3, PRINT HISTOGRAM OUTPUTS
C
      COMMON/AW/NPULSE(64),PSUM(64),PSUM2(64),PMAX(64),PMIN(64),
     *          PMEAN(64),PVAR(64),PSTD(64)
      COMMON/SPREAD/  PWHIST
      COMMON/UFHDAT/  UFCELL(64),XNCELL(64),NUFPTR(64)
      COMMON/UFHIST/ IPASS,NCHAN,DT
      INTEGER*4 P /14/
      INTEGER*2 STARS(80),BARS(119),PWHIST(64,51)
      DIMENSION PWRES(64)
      DATA STARS,BARS/80*'*',119*'-'/
      EQUIVALENCE (NCHAN,KCHAN)
      IF(IPASS.EQ.2)  GO TO 2000
      IF(IPASS.EQ.3)  GO TO 3000
C     INITIALIZATION PHASE...
      DO 3 L = 1,64
      NPULSE(L) = 0
      PSUM(L) = 0.
      PSUM2(L) = 0.0
      PMAX(L) = 0.0
      PMIN(L) = 1.0E30
      PMEAN(L) = 0.
      PVAR(L) = 0.
      PSTD(L) = 0.
      PWRES(L) = UFCELL(L)/XNCELL(L)
      DO 3 KCELL = 1,51
      PWHIST(L,KCELL) = 0
```

```
    3 CONTINUE
      RETURN
C     SECTION TO LOAD CURRENT DATA POINT...
 2000 NPULSE(NCHAN) = NPULSE(NCHAN) + 1
      PSUM(NCHAN) = PSUM(NCHAN) + DT
      PSUM2(NCHAN) = PSUM2(NCHAN) + DT*DT
      IF(DT.LT.PMIN(NCHAN))  PMIN(NCHAN) = DT
      IF(DT.GT.PMAX(NCHAN))  PMAX(NCHAN) = DT
      KROW = DT/PWRES(NCHAN)
      IF(KROW.LT.1)  KROW = 1
      IF(KROW.GT.50)  KROW = 51
      PWHIST(NCHAN,KROW) = PWHIST(NCHAN,KROW) + 1
      RETURN
C     SECTION TO PRODUCE HISTOGRAM FOR SPECIFIED CHANNEL...
C     FIND MAX NMBR OF OBSV IN CELL...
 3000 PWSCL =  0.0
      DO 51 JSCAN = 1,51
      IF(PWHIST(KCHAN,JSCAN).GT.PWSCL)  PWSCL = PWHIST(KCHAN,JSCAN)
   51 CONTINUE
      PW80 = AMAX1(1.,(PWSCL/80.))
C     DO PULSE WIDTH OUTPUT FOR SPECIFIED CHANNEL...
C     ADJUST LOGICAL UNIT NUMBER FOR PRINTER FOR GIVEN DATA...
      P = NUFPTR(NCHAN)
      IF(NPULSE(KCHAN).GT.2)  GO TO 3001
      IF(KCHAN.GT.15)  WRITE(P,80)  KCHAN,NPULSE(KCHAN)
      RETURN
 3001 FNP = NPULSE(KCHAN)
      PWMEAN = PSUM(KCHAN)/FNP
      PWVAR = (PSUM2(KCHAN)-(PSUM(KCHAN)*PSUM(KCHAN)/FNP))/(FNP-1.0)
C     ANTICIPATE NUMERICAL ROUND-OFF PROBLEMS...
      PWSTD = 0.0
      IF(PWVAR.GT.0.0)  PWSTD = SQRT(PWVAR)
      PMEAN(KCHAN) = PWMEAN
      PVAR(KCHAN) = PWVAR
      PSTD(KCHAN) = PWSTD
C     ABORT NORMAL HISTGM PRINTOUT FOR SONICS...
      IF(KCHAN.LT.12)  RETURN
C     ABORT NORMAL HISTGM PRINTOUT FOR MODE DATA...
      IF(KCHAN.LT.16)  RETURN
      WRITE(P,200)  FNP,PMAX(KCHAN),PMIN(KCHAN),PWMEAN,
     1              PWVAR,PWSTD,PWRES(KCHAN)
      WRITE(P,102)  BARS
      WRITE(P,100)  PW80
      WRITE(P,102)  BARS
      NSUM = 0
      DO 3003 JWORK = 1,51
      IWORK = PWHIST(KCHAN,JWORK)
      FWORK = IWORK
      NSUM = NSUM + IWORK
      FSUM = NSUM
      CPC = (FSUM/FNP)*100.
      CLIMIT = JWORK*PWRES(KCHAN)
      JOUT = FWORK/PW80
      IF(IWORK.GT.0)  GO TO 3005
      WRITE(P,101)  CLIMIT,IWORK,NSUM,CPC
      GO TO 3004
 3005 WRITE(P,101)  CLIMIT,IWORK,NSUM,CPC,(STARS(J),J=1,JOUT)
 3004 IF(NSUM.LT.NPULSE(KCHAN))  GO TO 3003
      IF(JWORK.LT.51)  WRITE(P,62)
      RETURN
 3003 CONTINUE
      RETURN
   62 FORMAT(' REMAINING ENTRIES ARE ALL ZERO...')
   80 FORMAT(/1X,'PULSE COUNT FOR CHANNEL ',I3,' IS ',I2,
     * ', HISTOGRAM DELETED')
  100 FORMAT(   1X,'CLASS       NUMBER   CUM       CUM      ',
     1  19X,'F R E Q U E N C Y  D I S T R I B U T I O N',/,
     2 1X,'UPPER       IN       TOTAL     PER      ',21X,
   3 '(EACH STAR = ',F9.1,' CBSERVATICNS)',/,
   4 1X,'LIMIT        CLASS    CASES     CENT      ')
 101 FORMAT(1X,E10.4,' ',I8,' ',I9,' ',F8.2,' ',80A1)
 102 FORMAT(1X,119A1)
 200 FORMAT(/1X,'NUMBER CF OBSERVATIONS = ',F6.0,/,
   1          1X,'MAXIMUM VALUE OBSERVED = ',E14.6,/,
   2          1X,'MINIMUM VALUE OBSERVED = ',E14.6,/,
   3          1X,'MEAN VALUE CF CATA = ',E14.6,/,
   4          1X,'VARIANCE CF CATA = ',E14.6,/,
   5          1X,'STANCARC CEVIATION OF CATA = ',E14.6,/,
   6          1X,'HISTCGRAM CELL WIDTH = ',E14.6,/)
     END
```

```
      SUBROUTINE HISTX(JUMP)
C
C     HISTX PRODUCES HEADINGS AND CALLS FOR HISTGM OUTPUTS AT THE END
C     OF EACH STUDY RUN.
C
      COMMON/TITLE/HEADER(18)
      COMMON/UFHIST/ IPASS,NCHAN,DATUM
      INTEGER*4 P /6/
      WRITE(P,43)HEADER
   43 FORMAT(1H1/10X,18A4///)
      IPASS = 3
      GOTO(1,2,3,4,5,8,402,402,952,954,956,1000,1500,402 ,402 ,1800,
     *     1900,2000),JUMP
    1 WRITE(P,411)
  411 FORMAT(26X,'HEADWAYS FOR F7')
      NCHAN = 16
      GOTO 401
    2 WRITE(P,422)
  422 FORMAT(26X,'HEADWAYS FOR F1')
      NCHAN = 17
      GOTO 401
    3 RETURN
    4 WRITE(P,444)
  444 FORMAT(18X,'HEADWAYS FOR R10 IN MOVING MODE')
      NCHAN = 19
      GOTO 401
    5 WRITE(P,455)
  455 FORMAT(18X,'HEADWAYS FOR  R1 IN MOVING MODE')
      NCHAN = 20
      GOTO 401
    8 WRITE(P,701)
  701 FORMAT(10X,'TRAVERSE TIME OF ALL RAMP VEHICLES BETWEEN R10 ENTRY A
     XND R1  EXIT')
      NCHAN = 23
      GCTC 401
  952 WRITE(P,953)
  953 FORMAT(10X,'DISTRIBUTION OF HIGHWAY ACCELERATION NOISE')
      NCHAN = 26
      GCTC 401
  954 WRITE(P,955)
  955 FORMAT(18X,'HEACWAYS FOR R1C IN STOPPED MCDES',/,
     * 18X,'(ALL VEHICLES ACRCSS R10 IN BEFORE STUDIES)')
      NCHAN = 21
      GCTC 401
  956 WRITE(P,957)
  957 FORMAT(18X,'HEACWAYS FOR  R1 IN STOPPED MCDES',/,
     *  18X,'(ALL VEHICLES ACROSS R1 IN BEFORE STUDIES)')
      NCHAN = 22
      GO TC 401
 1000 WRITE(P,1C01)
 1001 FCRMAT(18X,'HEACWAYS FOR FOA/B')
      NCHAN = 27
      GO TO 401
 1500 WRITE(P,1501)
 1501 FCRMAT(18X,'DISTRIBUTICN OF RAMP ACCELERATION NCISE',/,
     * 18X,'(ALL RAMP VEHICLES IN BEFORE STUDY, MM VEHICLES ONLY IN AFTE
     *R STUDY)')
      NCHAN = 28
      GC TC 401
 1800 WRITE(P,8600)
 8600 FORMAT(18X,'DISTRIBUTION OF FWY VEH LENGTHS AT F1')
      NCHAN = 41
      GC TC 401
 1900 WRITE(P,8601)
 8601 FORMAT(18X,'CISTRIBUTICN OF FWY VEH VELOCITIES AT F1')
      NCHAN = 42
      GO TC 401
 2000 WRITE(P,2C01)
```

```
2001 FORMAT(18X,'DISTRIBUTION OF FREEWAY GAPS MATCHED AT R1')
     NCHAN = 33
 401 CALL HISTGM                                                          HISTGM
 402 RETURN
     END
```

```
      SUBROUTINE INIT
C
C     INIT IS CALLED BY MAIN BEFORE EACH STUDY TO INITIALIZE DATA ARRAYS
C     AND WORKING STORAGE AREAS.
C
      COMMON/AA2/GC,FLAG,CAR1C
      COMMON/ACCEL/AM(120),AS(120),AC(120),LINE,LAST
      COMMON/ACCELR/  RAM(120),RAS(120),RAC(120),LINER
      COMMON/C/CARNO
      COMMON/CFLICT/  KRCNFL(18),KSMRED,KSGREC,
     *                N3SGM,N3SGUM,N3SGYL,N3MMM,N3MMUM,N3MMYL
      COMMON/CUTTY/  CIN(49),CCUT(49)
      COMMON/GBPROB/  NSGTRY(9),NSGOK(9),NMMTRY(9),NMMOK(9)
      COMMON/GBSHOW/  KGBPIC,TBANC,KGBBMM,KGBBSG ,XNMMB,XNSGB
      COMMON/EPUNCH/  METCUT(12),LINETA
      COMMON/EXT2/TTRCM,TTRDS,TTRCC,SSTRM(9),SSTRS(9),SSTRC(9),
     X            TTRVM,TTRVS,TTRVC,SSVM(9),SSVS(9),SSVC(9)
      COMMON/FIELD/CRCISP,CBGB,PTS,RED,AMBER,GREEN,
     1           VMRG,VBAR,C,MWC,MODE,GBMASK
      COMMON/IND1/TIME,LCOP,SENS,CODE,JMAX
      COMMON/IND2/ NE(49),FJ(49),CJ(49),NH,NR
      COMMON/KKK/KIN,KOUT,KSTRT
      COMMON/MPUNCH/  MRGCUT(20),MLINE
      COMMON/MRGCNT/  MERGES(8)
      COMMON/MULT/  TSTRT,TAX,FIRST
      COMMON/RCUT/TCT(4),JMCDE(4),TMODE(4),LOG(4)
      COMMON/RCUT2/  SGMLCG,MMMLOG,TSGMSK,TMMMSK,TOTSGM,TCTMMM
      COMMON/SEN/ INSENS(49)
      COMMON/STAT2/  VM(49),VS(49),VC(49)
      COMMON/STAT7/TIN(49),TOUT(49),TOC(49),TNOC(49),PTOC(49)
      COMMON/TAB/T1(49,7),T2(49,7),T3(49,7),T4(49,7),V(49,7),ETA(49,7),
     1 ETANO(49,7),LEN(49,7),ACC(49,7),CAR(49,7),D(49,7) ,
     2 STAT(49,7),WIRE(49,7)
      COMMON/TRAV/RAMPT(500)
      COMMCN/TRBANC/BW(9,12C),BWM,BWS,BWC,SBWM(9),SBWS(9),SBWC(9)
      CCMMCN/TRVD/TRDIST(9,12C),TRDM,TRDS,TRDC,STRM(9),STRS(9),STRC(9)
      COMMCN/TRVV/    TRVEL(9,120),TRVM,TRVS,TRVC,SVM(9),SVS(9),SVC(9)
      COMMCN/UFE/KRINHB,KFLAG,CLOCK,KFULL,KFINI,INITI8
      COMMCN/UFHIST/IPASS,KCHAN,CATUM
      COMMCN/UFSONC/KSCN,SCNCT
      COMMCN/XCUT/  XXXCUT(10CC,7)
      COMMON/XMCATA/ XMETA(60),XMT2(60),XMVEL(6C),XMLEN(6C),NXM
      REAL LEN
       REAL*4 KGBBMM(160),KGBBSG(160)
      INTEGER CAR1O,       CAR,CARNO,FJ,CJ,SENS,CODE,STAT,WIRE
      INTEGER*2  DRDISP(160),CBGB,PTS,RED,AMBER,GREEN,
     1             VMRG,VBAR,C,MWC,MODE,GBMASK
      LOGICAL            LAST,GC,FLAG,FIRST,LOG,SGMLOG,MMMLOG
C     VARIABLES FOR CCMMCN AA2...
      GO=.FALSE.
      FLAG=.FALSE.
      CAR1C=0
C     VARIABLES FOR CCMMON ACCEL...
      DO 15 I=1,120
      AM(I)=0.
      AS(I)=0.
   15 AC(I)=0.
      LINE=1
      LAST=.FALSE.
C     VARIABLES FOR CCMMON ACCELR...
      CO 16 I = 1,120
      RAM(I) = C.0
      RAS(I) = 0.0
   16 RAC(I) = C.0
      LINER = 1
C     VARIABLES FOR CCMMON C...
      CARNC=0
C     VARIABLES FOR CCMMON CFLICT...
```

```
      DO 3000 I = 1,18
 3000 KRCNFL(I) = 0
      KSMRED = 0
      KSGRED = 0
      N3SGM  = 0
      N3SGUM = 0
      N3SGYL = 0
      N3MMM  = 0
      N3MMUM = 0
      N3MMYL = 0
C     VARIABLES FOR COMMON CUTTY...
      DO 300 I = 1,49
      CIN(I) = 0.
  300 COUT(I) = 0.
C     VARIABLES FOR COMMON GBPROB...
      DO 2 I = 1,9
      NSGTRY(I) = 0
      NSGCK(I) = 0
      NMMTRY(I) = 0
    2 NMMCK(I) = 0
C     VARIABLES FOR COMMON GBSHOW...
      DO 8243 I = 1,160
      KGBBMM(I) = 0.
 8243 KGBBSG(I) = 0.
      XNMMB  = 0.
      XNSGB = 0.
C     VARIABLES FOR COMMON EPUNCH...
      LINETA = 1
C     VARIABLES FOR COMMON EXT2...
      TTRDM=0.
      TTRDS=0.
      TTRDC=0.
      DO 14 I=1,9
      SSTRM(I)=0.
      SSTRS(I)=0.
   14 SSTRC(I)=0.
      TTRVM=0.
      TTRVS=0.
      TTRVC=0.
      DO 114 I = 1,9
      SSVM(I)=0.
      SSVS(I)=0.
  114 SSVC(I)=0.
C     VARIABLES FOR COMMON FIELD...
      DBGB = 0
      PTS = 0
      RED = 0
      AMBER = 0
      GREEN = 0
      VMRG = 0
      VBAR = 0
      Q = 0
      MWC = 0
      MODE = 0
      GBMASK = 1
C     VARIABLES FOR COMMON INC1...
      JMAX=7
C     VARIABLES FOR COMMON INC2...
      DO 10 I=1,49
      NE(I)=0
      FJ(I)=1
   10 CJ(I)=0
C     VARIABLES FOR COMMON KKK...
      KIN=0
      KOUT=0
      KSTRT=0
C     VARIABLES FOR COMMON MPUNCH...
      MLINE = 1
```

```
C     VARIABLES FOR COMMON MRGCNT...
      DO 4000 I = 1,8
 4000 MERGES(I) = 0
C     VARIABLES FOR COMMON MULT...
      TSTRT = 0.0
      TAX = 14.0
      FIRST = .FALSE.
C     VARIABLES FOR COMMON ROUT...
      DO 3 I = 1,4
      TOT(I)=0.
      JMODE(I)=0
      TMODE(I)=0.
    3 LOG(I)=.FALSE.
C     VARIABLES FOR COMMON ROUT2...
      SGMLOG = .FALSE.
      MMMLOG = .FALSE.
      TSGMSK = 0.
      TMMMSK = 0.
      TOTSGM = 0.
      TOTMMM = 0.
C     VARIABLES FOR COMMON SEN...
      DO 80 I = 1,49
   80 INSENS(I)=0
C     VARIABLES FOR COMMON STAT2...
      DO 70 I=1,49
      VM(I)=0.
      VS(I)=0.
   70 VC(I)=0.
C     VARIABLES FOR COMMON STAT7...
      DO 30 I=1,49
      TIN(I)=0.
      TOUT(I)=0.
      TOC(I)=0.
      TNOC(I)=0.
   30 PTCC(I)=0.
C     VARIABLES FOR COMMON TAB...
      DO 20 I=1,49
      DO 20 J=1,JMAX
      ETA(I,J)=0.
      ETANC(I,J)=0.
      D(I,J)=0.
      T1(I,J)=0.
      T2(I,J)=0.
      T3(I,J)=0.
      T4(I,J)=0.
      V(I,J)=0.
      LEN(I,J)=0.
      ACC(I,J)=0.
      CAR(I,J)=0
      WIRE(I,J)=0
   20 STAT(I,J)=0
C     VARIABLES FOR COMMON TRAV...
      DO 50 I=1,500
   50 RAMPT(I)=0.
C     VARIABLES FOR COMMON TREAND...
      DO 81 I = 1,9
      SBWM(I)=0.
      SBWS(I)=0.
      SBWC(I)=0.
      DO 81 J = 1,120
   81 BW(I,J)=0.
      BWM=0.
      BWS=0.
      BWC=0.
C     VARIABLES FOR COMMON TRVC...
      DO 82 I = 1,9
      STRM(I)=0.
      STRS(I)=0.
      STRC(I)=0.
      DO 82 J = 1,120
   82 TRDIST(I,J)=0.
      TRDM=0.
      TRDS=0.
      TRDC=0.
C     VARIABLES FOR CCMMON TRVV...
      DC 201 I=1,9
      SVM(I) = 0.
      SVS(I) = 0.
      SVC(I) = 0.
      CC 201 J=1,120
  201 TRVEL(I,J)=0.
      TRVM = 0.0
      TRVS = 0.0
      TRVC = 0.0
C DO NCT INITIALIZE EVENT PROCESSING ON MULTIPLE STUDY RUNS...
      IF(LCOP.NE.0)  GC TO 500
C     VARIABLES FOR CCMMON UFE...
      KRINHB = 0
      KFLAG = 1
      INITI8 = 0
C     VARIABLES FOR CCMMON UFHIST...
  500 IPASS = 1
      KCHAN = 1
      DATUM = 0.0
      CALL HISTGM                                                      HISTGM
      IPASS = 2
C     VARIABLES FOR CCMMON UFSCNC...
      KSON = 1
C     VARIABLES FOR CCMMON XCUT...
      DC 1000 I = 1,1CCO
      DO 1CO0 J = 1,7
 1000 XXXCUT(I,J) = -1.
```

```
C      VARIABLES FOR COMMON XMDATA...
       DO 2000 I = 1,60
       XMETA(I) = 1.0E50
       XMT2(I) = 0.
       XMVEL(I) = 0.
 2000  XMLEN(I) = 0.
       NXM = 1
       RETURN
       END
```

```
      SUBROUTINE MODEXX
C
C     MODEXX IS CALLED TO MONITOR SYSTEM MODE AND MASKING ACTIVITY
C     EACH TIME NEW FIELD DISPLAY DATA IS AVAILABLE.
C
      COMMON/FIELD/DRDISP,DBGB,PTS,RED,AMBER,GREEN,
     1               VMRG,VBAR,C,MWC,MODE,GBMASK
      COMMON/IND1/TIME,LOOP,SENS,CODE,JMAX
      COMMON/RCUT/ TOTMM,TOTSG,TOTSM,TOTIN,JMM,JSG,JSM,JIN,
     1               TMM,TSG,TSM,TIN,MMLOG,SGLOG,SMLOG,INLOG
      COMMON/RCUT2/  SGMLOG,MMMLOG,TSGMSK,TMMMSK,TOTSGM,TOTMMM
      COMMON/UFHIST/ IPASS,NCHAN,CT
      INTEGER*2  DRDISP(160),DBGB,PTS,RED,AMBER,GREEN,
     1               VMRG,VBAR,C,MWC,MODE,GBMASK
      LOGICAL MMLOG,SGLOG,SMLOG,INLOG,SGMLOG,MMMLOG
      JUMP = 1 + MODE
      GO TO (60,30,50,40),JUMP
   60 IF(INLOG)  RETURN
C MODE CHANGE TO RE-INIT ON
      WRITE(6,200)  TIME
  200 FORMAT(40X,'INON ',F10.3)
      TIN = TIME
      INLOG = .TRUE.
      IF(SMLOG)  GO TO 5
      IF(SGLOG)  GO TO 25
      IF(MMLOG)  GO TO 15
      RETURN
   30 IF(SMLOG)  RETURN
C MODE CHANGE TO SM ON
      WRITE(6,105)TIME
  105  FORMAT(40X,'SMON ',F10.3)
      TSM=TIME
      SMLOG=.TRUE.
      IF(INLOG)  GO TO 300
      IF(SGLOG)GOTO 25
      IF(MMLOG)GOTO 15
      RETURN
   50 IF(SGLOG)  GO TO 5000
C MODE CHANGE TO SG ON
      WRITE(6,106)TIME
  106  FORMAT(40X,'SGON ',F10.3)
      TSG=TIME
      SGLOG=.TRUE.
      IF(INLOG)  GO TO 300
      IF(SMLOG)GOTO 5
      IF(MMLOG)GOTO 15
      RETURN
   40 IF(MMLOG)  GO TO 4000
C MODE CHANGE TO MM ON
      WRITE(6,104)TIME
  104  FORMAT(40X,'MMON ',F10.3)
      TMM=TIME
      MMLOG=.TRUE.
      IF(INLOG)  GO TO 300
      IF(SMLOG)GOTO 5
      IF(SGLOG)GOTO 25
      RETURN
C MODE CHANGE TO RE-INIT OFF
  300 TIN = TIME - TIN
         NCHAN = 12
         DT = TIN
      CALL HISTGM
      WRITE(6,201)  TIME
  201 FORMAT(40X,'INOFF',F10.3)
      INLOG = .FALSE.
      TOTIN = TOTIN + TIN
      JIN = JIN + 1
      RETURN
```

HISTGM

```
C MODE CHANGE TO SM OFF
    5  TSM=TIME-TSM
          NCHAN = 13
          DT = TSM
       CALL HISTGM                                                      HISTGM
       WRITE(6,102)TIME
  102   FORMAT(40X,'SMOFF',F10.3)
       SMLOG=.FALSE.
       TOTSM=TOTSM+TSM
       JSM=JSM+1
       RETURN
C MODE CHANGE TO SG OFF
   25  TSG=TIME-TSG
          NCHAN = 14
          DT = TSG
       CALL HISTGM                                                      HISTGM
       WRITE(6,103)TIME
  103   FORMAT(40X,'SGOFF',F10.3)
       SGLOG=.FALSE.
       TOTSG=TOTSG+TSG
       JSG=JSG+1
       IF(SGMLOG)  GO TO 2000
       RETURN
C MODE CHANGE TO MM OFF
   15  TMM=TIME-TMM
          NCHAN = 15
          DT = TMM
       CALL HISTGM                                                      HISTGM
       WRITE(6,101)TIME
  101   FORMAT(40X,'MMOFF',F10.3)
       MMLOG=.FALSE.
       TOTMM=TOTMM+TMM
       JMM=JMM+1
       IF(MMMLOG)  GO TO 3000
```

```
      RETURN
C     SG MASKED NOW
 5000 IF(GBMASK.EQ.0)  GO TO 5050
      IF(SGMLOG)  GO TO 2000
      RETURN
 5050 IF(SGMLOG)  RETURN
      TSGMSK = TIME
      SGMLOG = .TRUE.
      RETURN
C     MM MASKED NOW
 4000 IF(GBMASK.EQ.0)  GO TO 4040
      IF(MMMLOG)  GO TO 3000
      RETURN
 4040 IF(MMMLOG)  RETURN
      TMMMSK = TIME
      MMMLOG = .TRUE.
      RETURN
C     SG NOW UNMASKED...
 2000 TSGMSK = TIME - TSGMSK
      TOTSGM = TOTSGM + TSGMSK
      SGMLOG = .FALSE.
      RETURN
C     MM NOW UNMASKED...
 3000 TMMMSK = TIME - TMMMSK
      TOTMMM = TOTMMM + TMMMSK
      MMMLOG = .FALSE.
      RETURN
      END
      SUBROUTINE NOISE(CUTOUT,CUTIN)
C
C     NOISE IS CALLED FROM TRACK TO COMPUTE AND RECORD FREEWAY
C     VEHICLE ACCELERATION NOISE BETWEEN F7 AND F1.
C
      COMMON/ACCEL/AM(120),AS(120),AC(120),LINE,LAST
      COMMON/INC3/ I,J
      COMMON/PRT/ IPLOT,IHIST,IPRT1,IPRT4,INOISE,IXX(5),TMAX
      COMMON/TAB/T1(49,7),T2(49,7),T3(49,7),T4(49,7),V(49,7),ETA(49,7),
     1 ETANO(49,7),LEN(49,7),ACC(49,7),CAR(49,7),D(49,7) ,
     2 STAT(49,7),WIRE(49,7)
      COMMON/UFHIST/ IPASS,NCHAN,DATUM
      REAL LEN
      INTEGER CAR,STAT,WIRE
      LOGICAL LAST,CUTIN,CUTOUT
      DIMENSION PR(18)
      IF(CAR(I,J).EQ.0) RETURN
      MCAR=CAR(I,J)-1
      K=1+MOD(MCAR,120)
      IF(CAR(I,J).EQ.1)K=1
      IF(CUTOUT)GOTO 102
      AM(K)=AM(K)+ACC(I,J)
      AS(K)=AS(K)+ACC(I,J)*ACC(I,J)
      AC(K)=AC(K)+1.
      IF(I.NE.7)RETURN
C CAR(I,J) IS LEAVING F1...
      AM(K)=AM(K)/AC(K)
      AS(K)=SQRT(AS(K)/AC(K)-AM(K)*AM(K))
      NCHAN = 26
      DATUM = AS(K)
      CALL HISTGM                                                       HISTGM
      PR(LINE)=CAR(I,J)
      PR(LINE+1)=AM(K)
      PR(LINE+2)=AS(K)
      AM(K)=0.
      AS(K)=0.
      AC(K)=0.
      IF(LINE .GE.16) GCTO 10C
      LINE=LINE+3
      RETURN
  100 IF(INCISE.EQ.0)  GO TO 1C3
      WRITE(8,101)(PR(JJ),JJ=1,18)
  101 FORMAT( 6(F7.0,F7.2,F6.2) )
  103 LINE=1
  102 AM(K)=0.
      AS(K)=0.
      AC(K)=0.
      CUTCUT=.FALSE.
      RETURN
      END
      SUBROUTINE OUT
C
C     OUT IS CALLED BY TIMID TO PRINT RUN SUMMARY DATA FOR EACH CASE.
C
      COMMON/C/CARNO
      COMMON/CFLICT/  KRCNFL(18),KSMRED,KSGRED,
     *                N3SGM,N3SGUM,N3SGYL,N3MMM,N3MMUM,N3MMYL
      COMMON/GBPROB/  NSGTRY(9),NSGOK(9),NMMTRY(9),NMMOK(9)
      COMMON/GBSHOW/  KGBPIC,TBAND,KGBBMM,KGBBSG ,XNMMB,XNSGB
      COMMON/INDI/TIME,LOOP,SENS,CODE,JMAX
      COMMON/MRGCNT/  MERGES(8)
      COMMON/PRT/ IPLOT,IHIST,IPRT1,IPRT4,INOISE,IXX(5),TMAX
      COMMON/TITLE/HEADER(18)
      COMMON/UFHIST/ IPASS,NCHAN,DATUM
      COMMON/UFSONC/KSCN,SONDT
      COMMON/XCNTRL/  KWRITE,IBAFT
      COMMON/XCUT/  XXXCUT(1000,7)
      INTEGER*4  VICMAP(7,7),SENS,CODE,CARNO
      INTEGER*4 P /6/
       REAL*4 KGBBMM(160),KGBBSG(160)
C     FOLLOWING VARIABLE CONTROLS PRINT OF FREEWAY VEHICLE
C     ETA/PERSISTENCE MATRIX...
      DATA KPERST /0/
C**********************************************************************
C     THIS SECTION PRODUCES SUMMARY OUTPUT COMMON TO BOTH
C     BEFORE AND AFTER STUDIES...
      CALL SACTON                                                       SACTON
      KSCN = 2
      CALL SCNICS                                                       SCNICS
      IF(KPERST.EQ.1)  WRITE(P,103)  HEADER
      IF(KPERST.EQ.1)  WRITE(P,110)
      DO 2000 I = 1,CARNO
      IF(I.GT.1000)  GO TO 2000
      IF(XXXCUT(I,1).EQ.0.)  GO TO 2000
      XXXSUM = 0.
      DO 1999 L = 1,7
 1999 XXXSUM = XXXSUM + XXXCUT(I,L)
      IF(XXXSUM.GE.-6.1)  GO TO 1998
C     FLAG ROW NULL FOR SUBSEQUENT ANALYSIS...
      XXXCUT(I,1) = 0.
      GO TO 2000
 1998 IF(KPERST.EQ.0)  GO TO 2000
      WRITE(P,2001)  I,(XXXCUT(I,J),J=1,7)
 2000 CONTINUE
C     PREPARE 'VEHICLE-IN-SYSTEM PERSISTENCE TABLE'...
      DO 3000 I = 1,7
      DO 3000 J = 1,7
 3000 VIOMAP(I,J) = 0
      DO 5000 IROW = 1,CARNO
      IF(IROW.GT.1000)  GO TO 5000
C     RAMP VEHICLE ROWS HAVE ZERO IN COLUMN ONE...
      IF(XXXCUT(IROW,1).EQ.0.)  GO TO 5000
      DO 4000 KFROM = 1,7
      IF(XXXCUT(IROW,KFROM).LT.0.) GO TO 4000
      GO TO 4001
 4000 CONTINUE
      GO TO 5000
 4001 IF(KFROM.LT.7)  GO TO 4002
C        SPECIAL CASE ... CUTIN AT F7 (NO CORRESPONDING CUTOUT)
         VIOMAP(7,7) = VIOMAP(7,7) + 1
      GO TO 5000
 4002 KLOOK = KFROM + 1
      IF(XXXCUT(IROW,KLOOK).GT.0.)  GO TO 4003
      KTO = KFROM
      GO TO 4052
 4003 DO 4050 KTO = KLOOK,7
      IF(XXXCUT(IROW,KTO).GT.0.)  GO TO 4050
      GO TO 4051
 4050 CONTINUE
      KTO = 7
      GO TO 4052
 4051 KTO = KTO - 1
 4052 VIOMAP(KTO,KFROM) = VIOMAP(KTO,KFROM) + 1
 5000 CONTINUE
C     PUT OUT 'VEHICLE-IN-SYSTEM PERSISTENCE TABLE'...
      WRITE(P,103)  HEADER
      WRITE(P,5500)   VIOMAP(1,1)
      WRITE(P,5501)  (VIOMAP(2,J),J=1,2)
      WRITE(P,5510)  (VIOMAP(3,J),J=1,3)
      WRITE(P,5520)  (VIOMAP(4,J),J=1,4)
      WRITE(P,5530)  (VIOMAP(5,J),J=1,5)
      WRITE(P,5540)  (VIOMAP(6,J),J=1,6)
      WRITE(P,5550)  (VIOMAP(7,J),J=1,7)
      WRITE(P,7002)
      DO 7005 I = 1,18
      IOUT = I + 10
 7005 WRITE(P,7006)  IOUT,KRCNFL(I)
      IPASS = 3
C HIGHWAY NOISE DISTRIBUTION
      CALL HISTX(9)                                                     HISTX
C RAMP NOISE DISTRIBUTION
      CALL HISTX(13)                                                    HISTX
C MEANS OF HEADWAYS
      CALL HISTX(1)                                                     HISTX
      CALL HISTX(2)                                                     HISTX
      CALL HISTX(10)                                                    HISTX
      CALL HISTX(11)                                                    HISTX
      CALL HISTX(12)                                                    HISTX
C MEAN OF RAMP TRAVERSE TIME BETWEEN R10 AND R1
      CALL HISTX(6)                                                     HISTX
C     GAP MATCHES AT R1...
      CALL HISTX(18)
```

```
C     PUT OUT VEHICLE LENGTH DISTRIBUTION AT F1...
      CALL HISTX(16)                                                    HISTX
C     PUT OUT FWY VEH VEL DISTRIBUTION AT F1...
      CALL HISTX(17)                                                    HISTX
      IF(IBAFT.EQ.0)  RETURN
C*******************************************************************************
C     FOLLOWING SECTION FOR AFTER STUDIES ONLY...
C FINISH LAST SIGNAL LIGHT STATUS AND COMPUTE MODE DISTRIBUTIONS
C AND PRINT WITH MODE DURATIONS
      IPASS = 2
      CALL PRMODE                                                       PRMODE
C PRINT TRACKING DISTANCE AND RELATIVE VELOCITY MEANS
      IF(IXX(1).EQ.0)  WRITE(6,103)  HEADER
      CALL OUTX                                                         OUTX
C     PUT OUT GB BULB 'OCCUPANCY' DATA...
      WRITE(P,103)  HEADER
C     CONVERT ALL ON-COUNTS TO PERCENT-ON VALUES...
      DO 8000 K = 1,160
      IF(XNMMB.GT.0.)
     *KGBBMM(K) = (KGBBMM(K)/XNMMB)*100.
      IF(XNSGB.GT.0.)
     *KGBBSG(K) = (KGBBSG(K)/XNSGB)*100.
 8000 CONTINUE
      WRITE(P,8001)
      DO 8002 I = 1,8
      IGO = (I-1)*20 + 1
      ISTOP = IGO + 19
 8002 WRITE(P,8003)  IGO,ISTOP,(KGBBMM(K),K=IGO,ISTOP)
      WRITE(P,8004)
      DO 8005 I = 1,8
      IGO = (I-1)*20 + 1
      ISTOP = IGO + 19
 8005 WRITE(P,8003)  IGO,ISTOP,(KGBBSG(K),K=IGO,ISTOP)
      WRITE(P,103)  HEADER
      WRITE(P,222) N3SGM,N3SGUM,N3SGYL,N3MMM,N3MMUM,N3MMYL
C     PUT OUT PR(GB) VS. SENSOR NUMBER DATA...
      WRITE(P,200)
      DO 205 I = 1,9
      ISENS = I + 10
      PRSG = 0.0
      IF(NSGTRY(I).EQ.0.OR.NSGOK(I).EQ.0)  GO TO 210
      PRSG = FLOAT(NSGOK(I))/FLOAT(NSGTRY(I))
  210 PRMM = 0.0
      IF(NMMTRY(I).EQ.0.OR.NMMOK(I).EQ.0)  GO TO 205
      PRMM = FLOAT(NMMOK(I))/FLOAT(NMMTRY(I))
  205 WRITE(P,215)  ISENS,NSGTRY(I),NSGOK(I),PRSG,NMMTRY(I),NMMOK(I)
     *  ,PRMM
      WRITE(P,9000)
      WRITE(P,7000)
      WRITE(P,7001)  KSMRED,KSGRED
      CALL HISTX(4)                                                     HISTX
      CALL HISTX(5)                                                     HISTX
      RETURN
C*********************************************************************
   11 FORMAT(3E15.3)
  103 FORMAT(1H1,/,1X,18A4,//)
  110 FORMAT(1X,'VEHICLE PERSISTENCE MATRIX...',/)
  200 FORMAT(///,' OBSERVED GREEN BAND PROBABILITIES AT RAMP SENSORS...'
     * ,/,25X,'SG',28X,'MM',/,
     *  5X,'SENSOR',2(6X,'NVEH',4X,'NBANDS',8X,'PR'),/)
  215 FORMAT(1X,I10,2(2I10,F10.3))
  222 FORMAT(//,' ANALYSIS OF SYSTEM ACTIVITY AT R3 (YIELD SIGN CONTROL
     *SENSOR)',/, ' MODE',2(7X,'VEHICLE COUNT'),3X,'YIELD ACTIVATIONS',/
     *,5X,6X,'(MASKED STATE)',4X,'(UNMASKED STATE)     (UNMASKED ONLY)',
     */,'  SG ',3I20,/,'  MM ',3I20)
 2001 FORMAT(I5,7F10.3)
 5500 FORMAT(//,' VEHICLE PERSISTENCE TABLE...',//,
     *  26X,'ENTRY POINT',/,
     *  19X,'1     2     3     4     5     6     7',///,
     *  12X,'1  ',I5,/)
5501 FORMAT(12X,'2 ',2I6,/)
5510 FORMAT(12X,'3 ',3I6,/)
5520 FORMAT(5X,'EXIT   4 ',4I6,/)
5530 FORMAT(5X,'POINT  5 ',5I6,/)
5540 FORMAT(12X,'6 ',6I6,/)
5550 FORMAT(12X,'7 ',7I6,////)
7000 FORMAT(1X,'POTENTIAL ON-RAMP CONFLICTS DETECTED...',/)
7001 FORMAT(I3,' CARS RAN RED LIGHT IN SM MODE',/,
     *        I3,' CARS RAN RED LIGHT IN SG MODE',///)
7002 FORMAT(1X,'CONFLICTS DUE TO RAMP VEHICLE SPEED DROPS GREATER THAN
     *8 FEET/SEC/SEC ...',/, ' SENSOR',5X,'COUNT')
7006 FORMAT(1X,I6,I10)
8001 FORMAT(1X,'GREEN BAND DISPLAY BULB ACTIVITY ... PERCENT ON-TIME IN
     * MM',/,1X,'BULB NOS.',/)
8003 FORMAT(1X,I4,'-',I3,2X,20F6.2,/)
8004 FORMAT(///,
     *        1X,'GREEN BAND DISPLAY BULB ACTIVITY ... PERCENT ON-TIME IN
     * SG',/,1X,'BULB NOS.',/)
9000 FORMAT(///)
      END
      SUBROUTINE OUTX
C
C     OUTX IS CALLED BY OUT TO COMPLTE AND PRINT SUMMARY DATA FROM
C     GB TRACKING DONE DURING EACH RUN.
C
      COMMON/EXT2/TTRDM,TTRDS,TTRDC,SSTRM(9),SSTRS(9),SSTRC(9),
     X             TTRVM,TTRVS,TTRVC,SSVM(9),SSVS(9),SSVC(9)
      COMMON/PRT/ IPLOT,IHIST,IPRT1,IPRT4,INOISE,IXX(5),TMAX
      COMMON/TITLE/ HEADER(18)
      COMMON/TRBAND/BW(9,120),BWM,BWS,BWC,SBWM(9),SBWS(9),SBWC(9)
      COMMON/TRVD/TRDIST(9,120),TRDM,TRDS,TRDC,STRM(9),STRS(9),STRC(9)
      COMMON/TRVV/TRVEL(9,120),TRVM,TRVS,TRVC,SVM(9),SVS(9),SVC(9)
      COMMON/UFHIST/ IPASS,NCHAN,DATUM
      REAL BIG/99999./
      INTEGER*4  P0,P1,P2
      DIMENSION STRSQ(9) ,SVSQ(9),SSTRSQ(9)
C     ESTABLISH PRINTER REFERENCES...
      IF(IXX(1).EQ.0)  WRITE(6,104)
      IF(IXX(1).EQ.1)  GO TO 1000
         P0 = 6
         P1 = 6
         P2 = 6
      GO TO 2000
 1000    P0 = 10
         P1 = 11
         P2 = 12
C TRACKING DISTANCE, MM
 2000 DO 10 I=1,9
      STRSQ(I)=0.
      IF(STRC(I).EQ.0.)GOTO 9
      STRM(I)=STRM(I)/STRC(I)
      STRSQ(I)=SQRT(STRS(I)/STRC(I)-STRM(I)*STRM(I))
      GOTO 10
    9 STRM(I)=BIG
```

```
      STRSQ(I)=BIG
   10 CONTINUE
      IF(IXX(1).EQ.0)  WRITE(6,105)
      WRITE(P0,1) (STRM(I),I=1,9),(STRSQ(I),I=1,9)
      WRITE(P0,2)(STRS(I),I=1,9,2),(STRS(I),I=2,8,2)
      WRITE(P0,5)  STRC
C TRACKING DISTANCE SG MODE
   35 DO 40 I=5,9
      SSTRSQ(I)=0.
      IF(SSTRC(I).EQ.0.)GOTO 39
      SSTRM(I)=SSTRM(I)/SSTRC(I)
      SSTRSQ(I)=SQRT(SSTRS(I)/SSTRC(I)-SSTRM(I)*SSTRM(I))
      GOTO 40
   39 SSTRM(I)=BIG
      SSTRSQ(I)=BIG
   40 CONTINUE
      WRITE(P0,3)(SSTRM(I),I=5,9),(SSTRSQ(I),I=5,9)
      WRITE(P0,4)SSTRS(5),SSTRS(7),SSTRS(9),           SSTRS(6),SSTRS(8)
      WRITE(P0,6)  (SSTRC(I),I=5,9)
C RELATIVE VELOCITY, MM
   15 DO 20 I = 1,9
      SVSQ(I)=0.
      IF(SVC(I).EQ.0.)GOTO 19
           SVM(I)=SVM(I)/SVC(I)
           SVSQ(I)=SQRT(SVS(I)/SVC(I)-SVM(I)*SVM(I))
      GOTO 20
   19 SVM(I)=BIG
      SVSQ(I)=BIG
   20 CONTINUE
      IF(IXX(1).EQ.0)  WRITE(6,106)
           WRITE(P1,1)(SVM(I),I=1,9),(SVSQ(I),I=1,9)
      WRITE(P1,2) (SVS(I),I=1,9,2),(SVS(I),I=2,8,2)
      WRITE(P1,5)  SVC
C RELATIVE VELOCITY, SG MODE
```

```
   45 DO 50 I=5,9
      SSTRSQ(I)=0.
      IF(SSVC(I).EQ.0.)GOTO 49
      SSVM(I)=SSVM(I)/SSVC(I)
      SSTRSQ(I)=SQRT(SSVS(I)/SSVC(I)-SSVM(I)*SSVM(I))
      GOTO 50
   49 SSVM(I)=BIG
      SSTRSQ(I)=BIG
   50 CONTINUE
      WRITE(P1,3)(SSVM(I),I=5,9),(SSTRSQ(I),I=5,9)
      WRITE(P1,4)SSVS (5),SSVS (7),SSVS (9),          SSVS (6),SSVS (8)
      WRITE(P1,6) (SSVC(I),I=5,9)
C BAND WIDTH, MM
   25  DO 30 I=1,9
      SVSQ(I)=0.
      IF(SBWC(I).EQ.0.)GOTO 29
       SBWM(I)=SBWM(I)/SBWC(I)
       SVSQ(I)=SQRT(SBWS(I)/SBWC(I)-SBWM(I)*SBWM(I))
      GOTO 30
   29 SBWM(I)=BIG
      SVSQ(I)=BIG
   30 CONTINUE
      IF(IXX(1).EQ.0)  WRITE(6,107)
       WRITE(P2,1)(SBWM(I),I=1,9),(SVSQ(I),I=1,9)
      WRITE(P2,2)(SBWS(I),I=1,9,2),(SBWS(I),I=2,8,2)
      WRITE(P2,5)  SBWC
      RETURN
    1 FORMAT(//' MEAN MM',9(3X,F6.2)/' SIGMA  ',9(3X,F6.2) )
    2 FORMAT(' SUMSQ ',5(E15.9,3X)/16X,4(E15.9,3X))
    3 FORMAT(//' MEAN SG',36X,5(3X,F6.2)/' SIGMA  ',36X,5(3X,F6.2) )
    4 FORMAT(' SUMSQ ',36X,3(E15.9,3X)/52X,2(E15.9,3X))
    5 FORMAT(   ' COUNT  ',9(3X,F6.0),///)
    6 FORMAT(   ' COUNT  ',36X,5(3X,F6.0),///)
  104 FORMAT(1X,'SUMMARY OF VEHICLE TRACKING AGAINST GB FIELD DISPLAY',/
     *         '                 R9         R8         R7        R6B        R6A
     *  R5         R4         R3         R2',//)
 105 FORMAT(//'  TRACKING DISTANCE OF VEHICLE FROM LEADING EDGE OF GREE
    XN BAND')
 106 FCRMAT(//'  RELATIVE VELCCITY BETWEEN VEHICLE AND GREEN BAND')
 107 FORMAT( //'  GREEN BAND WIDTH (FEET)')
     END
```

```
      SUBRCUTINE PRINT (NN)
C
C     PRINT DOES THE CUTPUT FCR FWY AND RAMP VEH TRACKING WHEN THESE
C     CPTICNS ARE SELECTEC.
C
      COMMCN/C/CARNC
      COMMCN/IND1/TIME,LOOP,SENS,CCDE,JMAX
      COMMCN/INC2/ NE(49),FJ(49),CJ(49),NH,NR
      COMMCN/IND3/I,J
      COMMCN/SEN/ INSENS(49)
      COMMCN/STAT5/ IFJ,ICJ,EYE,NJ
      COMMCN/TAB/T1(49,7),T2(49,7),T3(49,7),T4(49,7),V(49,7),ETA(49,7),
     1 ETANO(49,7),LEN(49,7),ACC(49,7),CAR(49,7),D(49,7) ,
     2 STAT(49,7),WIRE(49,7)
      REAL LEN
      INTEGER EYE,STAT,WIRE,CAR,FJ,CJ,SENS,CCDE,CAR10
      GO TC (1C,20,30,40,5C),NN
   10 WRITE(6,777) I,J,NE(I),FJ(I),CJ(I),WIRE(I,J),STAT(I,J),INSENS(I),
     1 CAR(I,J),D(I,J),T3(I,J),T4(I,J),T1(I,J),T2(I,J),V(I,J),LEN(I,J),
     2 ETA(I,J),ETANO(I,J),ACC(I,J)
      RETURN
   20 RETURN
   30 RETURN
   40 WRITE(19,800)I,J,NE(I),FJ(I),CJ(I),WIRE(I,J),STAT(I,J),INSENS(I),
     1 CAR(I,J),D(I,J),T3(I,J),T3(EYE,NJ),V(I,J),ACC(I,J)
      RETURN
   50 RETURN
  777 FORMAT(8I3,I5,F7.0,9F9.3)
  800 FORMAT(8I3,I5,F7.0,2F9.3,18X,2F9.3)
      END
      SUBROUTINE PRMODE
C
C     THIS ROUTINE IS CALLED BY OUT TO RECORD THE LAST MODE AND
C     MASKING DATA, AND TO GENERATE SUMMARY INFORMATION ON THESE ITEMS.
C
      COMMON/AW/NPULSE(64),PSUM(64),PSUM2(64),PMAX(64),PMIN(64),
     *          PMEAN(64),PVAR(64),PSTD(64)
      COMMON/INDI/TIME,LOOP,SENS,CODE,JMAX
      COMMON/ROUT/ TOTMM,TOTSG,TOTSM,TOTIN,JMM,JSG,JSM,JIN,
     1             TMM,TSG,TSM,TIN,MMLOG,SGLOG,SMLOG,INLOG
      COMMON/ROUT2/  SGMLOG,MMMLOG,TSGMSK,TMMMSK,TOTSGM,TOTMMM
      COMMON/SPREAD/  PWHIST
      COMMON/TITLE/HEADER(18)
      COMMON/UFHIST/ IPASS,NCHAN,DT
      INTEGER  SENS,CODE
      INTEGER*2  PWHIST(64,51)
      INTEGER*4  P /6/
      LOGICAL MMLOG,SGLOG,SMLOG,INLOG,SGMLOG,MMMLOG
C THE LAST MODE DURATION OF THE RUN HAS NOT BEEN RECORDED.
      IF(INLOG)  GO TO 50
      IF(SMLOG)GOTO 30
      IF(SGLOG)GOTO 20
C MOVING MODE
      TMM=TIME-TMM
         NCHAN = 15
         DT = TMM
         CALL HISTGM                                                    HISTGM
      TOTMM=TOTMM+TMM
      JMM=JMM+1
      GOTO 40
C STOP GAP ACCEPTANCE MODE
   20 TSG=TIME-TSG
         NCHAN = 14
         DT = TSG
         CALL HISTGM                                                   HISTGM
      TOTSG=TOTSG+TSG
      JSG=JSG+1
      GOTC 40
C STOP METERING MCDE
   30 TSM=TIME-TSM
         NCHAN = 13
         CT = TSM
         CALL HISTGM                                                   HISTGM
      TOTSM=TOTSM+TSM
      JSM=JSM+1
      GO TC 40
C INITIALIZATICN MCDE
   50 TIN = TIME - TIN
         NCHAN = 12
         CT = TIN
         CALL HISTGM                                                   HISTGM
      TOTIN = TOTIN + TIN
      JIN = JIN + 1
C     PREPARE FINAL STATISTICS...
   40    IPASS = 3
         NCHAN = 12
         CALL HISTGM                                                   HISTGM
         NCHAN = 13
         CALL HISTGM                                                   HISTGM
         NCHAN = 14
         CALL HISTGM                                                   HISTGM
         NCHAN = 15
         CALL HISTGM                                                   HISTGM
      FRACIN = TOTIN/TIME * 1CC.0
      FRACSM = TOTSM/TIME * 1C0.0
      FRACSG = TOTSG/TIME * 1CC.0
      FRACMM = TOTMM/TIME * 1CC.0
C     PUT CUT TITLE ANC SKIP TC NEW PAGE...
```

```
      WRITE(P,100)  HEADER
      DO 200 I = 1,30
      IMIN = I * 2
  200 WRITE(P,205)  IMIN,(PWHIST(J,I),J=12,15)
      WRITE(P,206)  (PWHIST(J,51),J=12,15)
      WRITE(P,210)  TOTIN,TOTSM,TOTSG,TOTMM
      WRITE(P,220)  (PMEAN(J),J=12,15)
      WRITE(P,230)  (PSTD(J),J=12,15)
      WRITE(P,240)  JIN,JSM,JSG,JMM
      WRITE(P,250)  FRACIN,FRACSM,FRACSG,FRACMM
C     BAND MASKING ANALYSIS...
C     FINAL MASK TIME MAY NEED UPDATE...
      IF(SGMLOG)  GO TO 2000
      IF(MMMLOG)  GO TO 3000
      GO TO 500
 2000 TSGMSK = TIME - TSGMSK
      TOTSGM = TOTSGM + TSGMSK
      GO TO 500
 3000 TMMMSK = TIME - TMMMSK
      TOTMMM = TOTMMM + TMMMSK
  500 PSG = (TOTSGM/TIME) * 100.
      PMM = (TOTMMM/TIME) * 100.
      WRITE(P,550) TOTSGM,PSG,TOTMMM,PMM
      RETURN
  100 FORMAT(1H1,18A4,//,' DISTRIBUTION OF SYSTEM MODAL BEHAVIOR',//,
     *  16X,'CLASS',15X,'NUMBER IN CLASS FOR EACH MODE',/,
     *  16X,'LIMIT',11X,'INIT',13X,'SM',13X,'SG',13X,'MM',/)
  205 FORMAT(15X,I2,' MIN',4I15)
  206 FORMAT(15X,' 60MIN',4I15,//)
  210 FORMAT(' TOTAL TIME',/,' IN MODE',13X,4F15.3,/)
  220 FORMAT(' AVERAGE TIME',/,' IN MODE',13X,4F15.3,/)
  230 FORMAT(' STD OF TIME',/,' IN MODE',13X,4F15.3,/)
  240 FORMAT(' NUMBER OF CHANGES',/,' TO THIS MODE',8X,4I15,/)
  250 FORMAT(' PERCENT OF TOTAL',/,' TIME SPENT IN MODE',2X,4F15.1,/)
```

```
550 FORMAT(//  ,' ANALYSIS OF SYSTEM GREEN BAND MASKING BY MODES...',/
   * ,  ' SG, MASKED FOR ',F10.3,' SECONDS,OR', F7.3,' PERCENT OF TOTA
   *L TIME',/,
   *    ' MM, MASKED FOR ',F10.3,' SECONDS,OR', F7.3,' PERCENT OF TOTA
   *L TIME')
    END
```

```
      SUBROUTINE RNOISE
C
C     RNOISE IS CALLED FROM TRACK TO COMPUTE AND RECORD RAMP VEHICLE
C     ACCELERATION NOISE BETWEEN R10 AND R1.
C
      COMMON/ACCELR/AM(120),AS(120),AC(120),LINE
      COMMON/INC3/ I,J
      COMMON/PRT/ IPLOT,IHIST,IPRT1,IPRT4,INOISE,IXX(5),TMAX
      COMMON/TAB/T1(49,7),T2(49,7),T3(49,7),T4(49,7),V(49,7),ETA(49,7),
     1 ETANC(49,7),LEN(49,7),ACC(49,7),CAR(49,7),D(49,7) ,
     2 STAT(49,7),WIRE(49,7)
      COMMON/UFHIST/ IPASS,NCHAN,DATUM
      REAL LEN
      INTEGER CAR,STAT,WIRE
      INTEGER*4  Q/17/
      DIMENSION PR(18)
      IF(CAR(I,J).EQ.0) RETURN
      MCAR=CAR(I,J)-1
      K=1+MOD(MCAR,120)
      IF(CAR(I,J).EQ.1)K=1
      AM(K)=AM(K)+ACC(I,J)
      AS(K)=AS(K)+ACC(I,J)*ACC(I,J)
      AC(K)=AC(K)+1.
      IF(I.NE.20)  RETURN
C CAR(I,J) IS LEAVING R1...
      AM(K)=AM(K)/AC(K)
      AS(K)=SQRT(AS(K)/AC(K)-AM(K)*AM(K))
      NCHAN = 28
      DATUM = AS(K)
      CALL HISTGM                                                   HISTGM
      PR(LINE)=CAR(I,J)
      PR(LINE+1)=AM(K)
      PR(LINE+2)=AS(K)
      AM(K)=0.
      AS(K)=0.
      AC(K)=0.
      IF(LINE .GE.16) GCTO 10C
      LINE=LINE+3
      RETURN
  100 IF(INCISE.EQ.0)   GO TC 1C2
      WRITE(Q,101)(PR(JJ),JJ=1,18)
  101 FORMAT( 6(F7.0,F7.2,F6.2) )
  102 LINE = 1
      AM(K)=0.
      AS(K)=0.
      AC(K)=0.
      RETURN
      END
      SUBROUTINE SACTON
C
C     SACTON IS CALLED BY OUT AT THE END OF EACH RUN TO GENERATE
C     AND PRINT SUMMARY DATA ON SENSOR ACTIVITY.
C
      COMMON/AW/NPULSE(64),PSUM(64),PSUM2(64),PMAX(64),PMIN(64),
     *          PMEAN(64),PVAR(64),PSTD(64)
      COMMON/CONVRT/SNAME(65),NSENHT(65)
      COMMON/CUTTY/  CIN(49),COUT(49)
      COMMON/STAT2/  VM(49),VS(49),VC(49)
      COMMON/STAT7/TIN(49),TOUT(49),TOC(49),TNCC(49),PTOC(49)
      COMMON/TITLE/ HEADER(18)
      INTEGER*4  P  /6/
C     ARRAY TO GIVE OPERATING ORDER FOR SENSOR OUTPUT...
      DIMENSION IOUT(65)
      DATA IOUT/ 16,15,14,13,12,11,10, 9, 8, 7, 6, 5, 4, 3,
     1          30,32,31, 1,28,27,22,23,26,25,46,24,21,
     2          20,19,18,17,48,47,45,44,43,42,33,
     3          37,41,40,39,38,36,35,34,
     4          52,51,64,54,55,50,63,62,49,57,56,59,58,61,60,
     5          2,29,53,65/
      WRITE(P,1) HEADER
      DO 30 I=1,49
      IF(VC(I).EQ.0.) GOTO 30
      VM(I)=VM(I)/VC(I)
      VS(I)=SQRT(VS(I)/VC(I) - VM(I)*VM(I))
   30 CONTINUE
      DO 35 I=1,49
      PP=TCC(I)+TNCC(I)
      IF(PP.EQ.0.) GOTO 35
      PTOC(I)=(100.*TCC(I)) / PP
   35 CONTINUE
C     PUT OUT DATA FOR FAR FREEWAY LANE...
      WRITE(P,50)
      WRITE(P,20)SNAME(59),SNAME(58),SNAME(60),SNAME(62),SNAME(49)
      WRITE(P,21)NSENHT(59),NSENHT(58),NSENHT(60),NSENHT(62),NSENHT(49)
      WRITE(P,22)  VM(44),VM(49)
      WRITE(P,22)  VS(44),VS(49)
      WRITE(P,23)  PTCC(46)
C     PUT CUT DATA FOR CENTER FREEWAY LANE...
      WRITE(P,20)SNAME(57),SNAME(56),SNAME(61),SNAME(50),SNAME(63)
      WRITE(P,21)NSENHT(57),NSENHT(56),NSENHT(61),NSENHT(50),NSENHT(63)
      WRITE(P,22)  VM(43),VM(48)
      WRITE(P,22)  VS(43),VS(48)
      WRITE(P,23)  PTCC(45)
C     PUT CUT DATA FOR SHOULDER FREEWAY LANE...
      WRITE(P,40) (SNAME (ICUT(K)),K=1,14),SNAME (54),SNAME (55)
      WRITE(P,41) (NSENHT(ICUT(K)),K=1,14),NSENHT(54),NSENHT(55)
      WRITE(P,42)  (VM(I),I=1,7),VM(47)
      WRITE(P,42)  (VS(I),I=1,7),VS(47)
      WRITE(P,24)  (CIN(I) ,I=1,7)
      WRITE(P,25)  (CCUT(I),I=1,7)
C     PUT CUT DATA FOR SONIC DETECTORS...
      WRITE(P,50)
      WRITE(P,40) (SNAME (ICUT(K)),K=28,38)
      WRITE(P,41) (NSENHT(ICUT(K)),K=28,38)
      WRITE(P,41)  (NPULSE(I),I=1,11)
      WRITE(P,43)  (PMEAN(I),I=1,11)
      WRITE(P,43)  ( PSTD(I),I=1,11)
C     PUT CUT DATA FOR MERGE AREA PRESENCE DETECTORS...
      WRITE(P,50)
      WRITE(P,40) (SNAME (ICUT(K)),K=39,46)
      WRITE(P,41) (NSENHT(ICUT(K)),K=39,46)
      WRITE(P,43)  (PTCC(I),I=21,28)
      WRITE(P,43)  (VM(I),I=21,28)
      WRITE(P,43)  (VS(I),I=21,28)
      WRITE(P,44)  (CIN (I),I=21,28)
      WRITE(P,45)  (CCUT(I),I=21,28)
```

```
C     PUT OUT DATA FOR RAMP PRESENCE DETECTORS...
      WRITE(P,50)
      WRITE(P,40) (SNAME (ICUT(K)),K=15,27)
      WRITE(P,41) (NSENHT(IOUT(K)),K=15,27)
      WRITE(P,43)  (PTCC(I),I= 8,20)
      WRITE(P,43)  (VM(I),I= 8,20)
      WRITE(P,43)  (VS(I),I= 8,20)
      WRITE(P,46)  (CIN (I),I=8,20)
      WRITE(P,47)  (CCUT(I),I=8,20)
C     PUT OUT DATA FOR EVALUATION DETECTORS...
      WRITE(P,50)
      WRITE(P,40) (SNAME (ICUT(K)),K=47,49)
      WRITE(P,41) (NSENHT(ICUT(K)),K=47,49)
      WRITE(P,43)  PTCC(41),PTOC(42),PTOC(40)
C     PUT OUT DATA FOR NUMBER OF FIELD DISPLAY DATA BLOCKS PROCESSED...
      WRITE(P,50)
      WRITE(P,40) SNAME(65)
      WRITE(P,41)NSENHT(65)
      WRITE(P,50)
      WRITE(P,60)
      RETURN
    1 FORMAT(1H1,18A4,//,' REPORT OF SENSOR CHANNEL ACTIVITIES...',//)
   20 FORMAT(//,43X,2(3X,A4),31X,A4,7X,2(3X,A4))
   21 FORMAT(   43X,2(2X,I5),30X,I5,7X,2(2X,I5))
   22 FORMAT(43X,F14.3,42X,F14.3)
   23 FORMAT(85X,F7.3)
   24 FORMAT(1X,7F14.0,'  CUTINS')
   25 FORMAT(1X,7F14.0,'  CUTOUTS')
   40 FORMAT(//,1X,16(3X,A4))
   41 FORMAT(   1X,16(2X,I5))
   42 FORMAT(1X,8F14.3)
   43 FORMAT(1X,13F7.3)
   44 FORMAT(1X, 8F7.0,'  CUTINS')
   45 FORMAT(1X, 8F7.0,'  CUTOUTS')
```

```
46 FORMAT(1X,13F7.0,'  CUTINS')
47 FORMAT(1X,13F7.C,'  CUTOUTS')
50 FORMAT(1X,112('-'))
60 FORMAT(/////,41X,'DATA CRGANIZATICN ABOVE IS...',/,
  *  41X,'VEL SENSCR NAME',11X,'PRES SENSOR NAME',/,
  *   41X,'NLOOP1   NLOOP2',16X,'COUNT',/,
  *   45X,'VEL MEAN',19X,'CCCUPANCY',/,
  *   45X,'VEL STC ',19X,'VEL MEAN',/, 72X,'VEL STD')
   END
```

```
      SUBROUTINE SONICS
C
C     SONICS IS CALLED BY TIMIC EACH TIME A NEW PULSE COMPLETION
C     IS REPORTED BY A SONIC DETECTOR.  RAMP VEHICLE LATERAL
C     DISPLACEMENTS ARE COMPUTED AND RECORDED.  AT THE END OF EACH RUN,
C     SONICS PRODUCES A TABLE OF VEHICLE DISPLACEMENT DATA.
C
      COMMON/AW/NPULSE(64),PSUM(64),PSUM2(64),PMAX(64),PMIN(64),
     *          PMEAN(64),PVAR(64),PSTD(64)
      COMMON/IND1/  TIME,LOOP,SENS,CODE,JMAX
      COMMON/SPREAD/  PWHIST
      COMMON/TITLE/HEADER(18)
      COMMON/UFHIST/IPASS,INDEX,FEET
      COMMON/UFSONC/KSON,SONCT
      INTEGER*4  P  /6/
      INTEGER  SENS,CODE
      INTEGER*2  PWHIST(64,51)
C     DISTANCE FROM CURB TO LANE LINE FOR EACH SONIC STATION...
C     ( SONIC HEADS ARE 1 FOOT BACK FROM CURB )
      REAL OFFSET(11) /17.75,15.08,2*14.,3*14.166,14.,12.5,8.5,2.75/
C     WIDTH OF FREEWAY SHOULDER LANE...
      DATA XLANE / 12.0 /
C     AVERAGE ASSUMED CAR WIDTH...
      DATA WIDTH / 6.00 /
      REAL FMAX(11) / 30.,27.,6*26.,25.,21.,15. /
      INTEGER*2  JBIG(30) / 15*11,6*10,4*9,8,2,1,1,1 /
C     BRANCH TO OUTPUT SEGMENT, IF APPROPRIATE...
      IF(KSON.EQ.2)  GO TO 500
C     GO BACK IF BOP EVENT...
      IF(CODE.NE.6)  RETURN
C     INTERNAL  CODES FOR SONICS ARE 29(S1) THRU 39(S11)...
      INDEX = SENS - 28
C     DO PROCESSING FOR SINGLE REPORTED SONIC PULSE COMPLETION...
C     NOTE... QUANTITY COMPUTED IS SEPARATION OF LEFT SIDE OF VEHICLE
```

```
C     FROM LEFT SIDE OF FREEWAY SHOULDER LANE...
      FEET = OFFSET(INDEX) - (39.931 - 521.55*SONDT) - WIDTH + XLANE
      IF(FEET.GT.FMAX(INDEX))  RETURN
C     INHIBIT SONIC REPORT FOR ASSUMED SHOULDER LANE VEHICLES...
      IF(FEET.LT.8.0)  RETURN
      CALL HISTGM                                                       HISTGM
      RETURN
C     OUTPUT PHASE...
  500 WRITE(P ,1)  HEADER                                               SONICS
      IPASS = 3
C     FOLLOWING LOOP PREPARES SUMMARY STATISTICS...
      DO 550 INDEX = 1,11
      CALL HISTGM                                                       HISTGM
  550 CONTINUE
      WRITE(P,600)
      WRITE(P,601)  (IHEAD,IHEAD=1,11)
      DO 650 KCUT = 1,30
      IF(KCUT.EQ.1)  WRITE(P,700)
      IF(KCUT.EQ.13)  WRITE(P,700)
      JLIMIT = JBIG(KCUT)
  650 WRITE(P,651)  KCUT,(PWHIST(J,KOUT),J=1,JLIMIT)
      WRITE(P,660)  (NPULSE(J),J=1,11)
      WRITE(P,665)  ( PMEAN(J),J=1,11)
      WRITE(P,670)  (  PSTD(J),J=1,11)
      RETURN
    1 FORMAT(1H1,18A4,//)
  600 FORMAT(' DISTRIBUTION OF SEPARATION OF LEFT SIDE OF RAMP VEHICLES
     *FROM LEFT BOUNDARY OF FREEWAY SHOULDER LANE...',/)
  601 FORMAT(2X,'DISTANCE',46X,'SONIC DETECTOR NUMBER',/,
     *       3X,'(FEET)',3X, 11(4X,I2,4X),/)
  651 FORMAT(5X,I2,4X, 11(3X,I4,3X))
  660 FORMAT(
     *  /,    ' COUNT      ',11(3X,I4,3X),/)
  665 FORMAT(' MEAN       ',11(1X,F8.3,1X),/)
```

```
670 FORMAT('  STD      ',11(1X,F8.3,1X))
700 FORMAT(1X,120('-'))
    END
```

```
      SUBROUTINE TIMIC
C
C     TIMIC SCHEDULES DATA TAPE PROCESSING FOR EACH CASE AND CALLS
C     FOR SUMMARY OUTPUT IF REQUESTED.
C
C     TIMING DATA VARIABLES...
C     'ENDT'  = TIME SINCE THE LAST RE-INIT.
C     'TIME'  = ELAPSED TIME FROM BEGINNING OF STUDY.
C     'TTOTAL'= ELAPSED TIME PRIOR TO PREVIOUS RE-INIT.
C
      COMMON/CALNDR/  IDATE(6),MILTYM,IPUNCH,IMRGPN,TDROP
      COMMON/CIPHER/  S,CI,CO
      COMMON/CONVRT/SNAME(65),NSENHT(65)
      COMMON/EPUNCH/  METCUT(12),LINETA
      COMMON/EVENTS/ ETABLE(1000,3),IETROW
      COMMON/FIELD/DRDISP,DBGB,PTS,RED,AMBER,GREEN,
     1              VMRG,VBAR,C,MWC,MODE,GBMASK
      COMMON/GBSHOW/  KGBPIC,TBAND,KGBBMM,KGBBSG ,XNMMB,XNSGB
      COMMON/INC1/TIME,LOOP,SENS,CODE,JMAX
      COMMON/MPUNCH/  MRGCUT(20),MLINE
      COMMON/MULT/  TSTRT,TAX,FIRST
      COMMON/PRT/ IPLCT,IHIST,IPRT1,IPRT4,INOISE,IXX(5),TMAX
      COMMON/UFE/KRINHB,KFLAG,CLOCK,KFULL,KFINI,INITI8
      COMMON/UFSONC/KSCN,SCNDT
      COMMON/XCNTRL/  KWRITE,IBAFT
      DIMENSION SHIST(11)
      INTEGER SENS,CODE
      INTEGER*4 P /13/  ,  Z /16/  ,  KDISC /20/
      INTEGER*2  DRDISP(160),DBGB,PTS,RED,AMBER,GREEN,
     1              VMRG,VBAR,C,MWC,MODE,GBMASK ,S(64),CI(64),CO(64)
       REAL*4 KGBBMM(160),KGBBSG(160)
      LOGICAL FIRST
      DATA XXINIT/'INIT'/
C INITIAL ENTRY OR CONTINUATION
```

```
      IF(LCCP.EQ.0)  GO TO 1
      IREC = 1
      NETSUM = 0
      IRENIT = 0
      IF(IGC.LE.IETROW)  GO TO 5000
      IGC = 1
      GO TO 5
    1 IREC = 0
      IGC = 1
      NETSUM = 0
      ENDT = 0.0
      IRENIT = 0
      TTOTAL = 0.0
      DO 3 I = 1,11
    3 SHIST(I) = 0.0
    5 REWIND KDISC
      CALL EVENT                                                    EVENT
      IREC = IREC + 1
      REWIND KDISC
      IF(KWRITE.EQ.1)  WRITE(Z,99) IETROW,CLOCK,KFULL,KFINI,KRINHB
      IF(IETROW.EQ.0)  GO TO 40
 5000 DO 2010 I = IGC,IETROW
         KSCHAN = ETABLE(I,1)
         TIMEXX = ETABLE(I,3)
         TIME = TIMEXX + TTOTAL - TDROP
      IF(ETABLE(I,2).EQ.1.)  NSENHT(KSCHAN) = NSENHT(KSCHAN) + 1
      IF(FIRST) GOTO 14
      FIRST=.TRUE.
      TSTRT=TIME
      TMAX=TIME+TMAX
   14 IF(KSCHAN.LT.65)  GO TO 2009
      IF(KSCHAN.EQ.999) GO TO 2090
      READ(KDISC)  DRDISP,DBGB,PTS,RED,AMBER,GREEN,
     1            VMRG,VBAR,C,MWC,MODE,GBMASK
```

```
C     SAVE TIME CURRENT FIELD DATA WAS RECORDED...
      TBAND = TIME
C     UPDATE GB DISPLAY 'BULB-ON' COUNTS...
      IF(MODE.LT.2)  GO TO 1718
      IF(MODE.LT.3)  GO TO 1720
C     MODE IS MM, UPDATE COUNTS...
 1730 XNMMB = XNMMB + 1.
      DO 1731 KGBB = 1,160
 1731 KGBBMM(KGBB) = CRDISP(KGBB) + KGBBMM(KGBB)
      GO TO 1718
C     MODE IS SG,  UPDATE COUNTS...
 1720 XNSGB = XNSGB + 1.
      DO 1721 KGBB = 1,160
 1721 KGBBSG(KGBB) = CRDISP(KGBB) + KGBBMM(KGBB)
 1718 IF(IPLOT.EQ.0)  CALL MODEXX                                  MODEXX
      IF(KWRITE.EQ.0)  GO TO 30
      WRITE(Z,98)  I,(ETABLE(I,J),J=1,3),SNAME(KSCHAN),CRDISP
      WRITE(Z,800)MWC,CBGB,PTS,RED,AMBER,GREEN,VMRG,VBAR,Q,MODE,GBMASK
      GO TO 30
 2090 WRITE(6,1001) ENDT,TIME
      IF(KWRITE.EQ.1) WRITE(Z,98) I,(ETABLE(I,J),J=1,3),XXINIT
      TTOTAL = TTOTAL + ENDT
      IRENIT = IRENIT + 1
      GO TO 30
 2009 IF(KWRITE.EQ.1) WRITE(Z,98) I,(ETABLE(I,J),J=1,3),SNAME(KSCHAN)
      IF(IPLOT.EQ.1)  GO TO 30
C     PRIMARY SENSOR PROCESSING HERE... T1,T2,T3,T4,TIN,TOUT,SONICS
      SENS = S(KSCHAN)
      IF(SENS.EQ.0)  GO TO 30
      IF(ETABLE(I,2).EQ.0.)  CODE = CO(KSCHAN)
      IF(ETABLE(I,2).EQ.1.)  CODE = CI(KSCHAN)
      IF(SENS.LT.29.OR.SENS.GT.39)  GO TO 18
      SONDT = TIME - SHIST(SENS-28)
      SHIST(SENS-28)  = TIME
      CALL SONICS                                                    SONICS
      GO TO 30
   18 CALL TRACK                                                     TRACK
   30 NETSUM = NETSUM + 1
      IF(TIME.GE.TMAX)  GO TO 40
      ENDT = TIMEXX
 2010 CONTINUE
C      RESTORE DO LOOP START POINT AFTER CONTINUATION ENTRY...
      IGO = 1
      IF(KFINI.NE.1)  GO TO 5
C     SAVE RESTART POSITION IN ETABLE FOR NEXT RUN...
   40 IGO = I + 1
      IF(IPLOT.EQ.1)  GO TO 6001
C     PUNCH REMAINING ENTRIES IN FWY VEH ETA OUTPUT BUFFER
      IF(IMRGPN.EQ.0)  GO TO 6000
      IF(LINETA.EQ.1)  GO TO 5999
      MSTOP = LINETA - 1
      WRITE(23,5002)  (METOUT(MOUT),MOUT=1,MSTOP)
C     PUNCH REMAINING ENTRIES IN MERGE AREA SENSOR HIT OUTPUT BUFFER...
 5999 IF(MLINE.EQ.1)  GO TO 6000
      MSTOP = MLINE - 1
      WRITE(22,5001)  (MRGOUT(MOUT),MOUT=1,MSTOP)
 6000 CALL OUT                                                       OUT
 6001 WRITE(6,900)  TTOTAL,ENDT,TIME,TMAX
      WRITE(6,901)  IRENIT
      WRITE(6,102) IREC
      WRITE(6,902) IETROW,IGO
      WRITE(6,101)  NETSUM
      WRITE(6,200)  NSENHT(4),NSENHT(31)
C     ACCUMULATE TIME BASE FOR PUNCHED OUTPUT...
      TDROP = TDROP + TIME
      RETURN
   98 FORMAT(1X,I5,2F4.0, F10.3,1X,1A4,2X,80I1,/,31X,80I1)
   99 FORMAT( / ,5X,'IETROW', 5X,'CLOCK',' KFULL',' KFINI',' KRINHB',
    1  /,   1X,I10,F10.3,2I6,I7,/)
  101 FORMAT(1X,I10,' EVENTS PROCESSED',/)
  102 FORMAT(1X,I10,' RECORDS READ',/)
  200 FORMAT(/,1X,'STUDY PERIOD FLOWS..., F1-A = ',I10,', R10 = ',I10)
  800 FORMAT(  31X,
    1           'MWC',3X,'CBGB',4X,'PTS',4X,'RED',2X,'AMBER',2X,'GREEN',
    2  3X,'VMRG',3X,'VBAR',6X,'Q',3X,'MODE GBMASK',/,27X,11I7)
  900 FORMAT(//,' TTOTAL,ENDT,TIME,TMAX = ',4F12.3,//)
  901 FORMAT(1X,'NMBR OF RE-INITS FOR THIS CASE = ',I5,/)
  902 FORMAT(' IETROW,IGO = ',2I5,/)
 1001 FORMAT(1X,'REINITIALIZATION - SECONDS',2F10.3)
 5001 FORMAT(10(I2,I6))
 5002 FORMAT(4(3I6))
      END
      SUBROUTINE TRACK
C
C     TRACK IS CALLED FOR EACH LOOP SENSOR EVENT TO PERFORM VEHICLE
C     TRACKING AND TO COLLECT OPERATING DATA ON THE GB SYSTEM.
C
      COMMON/AA2/GC,FLAG,CAR10
      COMMON/C/CARNO
      COMMON/CALNDR/  IDATE(6),MILTYM,IPUNCH,IMRGPN,TDROP
      COMMON/CFLICT/  KRCNFL(18),KSMRED,KSGRED,
     *                N3SGM,N3SGUM,N3SGYL,N3MMM,N3MMUM,N3MMYL
      COMMON/CONVRT/SNAME(65),NSENFT(65)
      COMMON/CUTTY/  CIN(49),COUT(49)
      COMMON/FIELD/DRDISP,DBGB,PTS,RED,AMBER,GREEN,
     1              VMRG,VBAR,C,MWC,MODE,GBMASK
      COMMON/GBSHOW/  KGBPIC,TBAND,KGBBMM,KGBBSG ,XNMMB,XNSGB
      COMMON/IND1/TIME,LOOP,SENS,CODE,JMAX
      COMMON/IND2/ NE(49),FJ(49),CJ(49),NH,NR
      COMMON/IND3/I,J
      COMMON/KKK/KIN,KOUT,KSTRT
      COMMON/MPUNCH/  MRGOUT(20),MLINE
      COMMON/MULT/  TSTRT,TAX,FIRST
      COMMON/OLDSTF/  PV(49,7),PT(49,7)
      COMMON/PRT/ IPLCT,IHIST,IPRT1,IPRT4,INOISE,IXX(5),TMAX
      COMMON/SEN/ INSENS(49)
      COMMON/STAT2/  VM(49),VS(49),VC(49)
      COMMON/STAT5/ IFJ,ICJ,EYE,NJ
      COMMON/STAT7/TIN(49),TOUT(49),TOC(49),TNOC(49),PTOC(49)
      COMMON/TAB/T1(49,7),T2(49,7),T3(49,7),T4(49,7),V(49,7),ETA(49,7),
     1 ETANO(49,7),LEN(49,7),ACC(49,7),CAR(49,7),D(49,7) ,
     2 STAT(49,7),WIRE(49,7)
      COMMON/TRAV/RAMPT(500)
      COMMON/UFHIST/ IPASS,NCHAN,TEMP
      COMMON/XCNTRL/  KWRITE,IBAFT
      COMMON/XCUT/  XXXCUT(1000,7)
      REAL LEN
      INTEGER CAR10,STAT,CAR,CARNO,CJM,WIRE,EYE,FJ,CJ,SENS,CODE
      INTEGER*2  DRDISP(160),DBGB,PTS,RED,AMBER,GREEN,
     1              VMRG,VBAR,G,MWC,MODE,GBMASK
       REAL*4 KGBBMM(160),KGBBSG(160)
      LOGICAL LAST,FIRST,CUTIN,CUTOUT,GO,FLAG,RAMP
      DIMENSION        DIST(49),DM(49),DS(49),GAGE(49)
C DIST = DISTANCE FROM FIRST SENSOR ON HIGHWAY OR RAMP TO SENSOR AT T3
      DATA DIST /0.,200.,400.,600.,800.,1000.,1200.,
     1 0.,420.,490.,560.,630.,700.,740.,770.,840.,910.,980.,1050.,1120.,
     2 1130.,1170.,1210.,1250.,1290.,1330.,1370.,1410.,21*10000./
C DM = DISTANCE FROM SENSOR AT T2 TO MERGE POINT
      DATA DM/1584.,1384.,1184., 984.,784.,584.,384.,
     1 1304.,884.,814.,744.,674.,604.,594.,564.,494.,424.,354.,284.,
     2  214.,204.,164.,124.,84.,44.,4.,-36.,-76.,21*10000./
C DS=DISTANCE BETWEEN SENSOR I AT T2 OR TOUT AND SENSOR I+1 AT T3 OR TIN
      DATA DS/7*200.,420.,4*70.,40.,30.,5*70.,10.,7*40.,22*10000./
C GAGE = GAGE LENGTH ASSOCIATED WITH SENSOR PAIR I
      DATA GAGE/20*20.,29*20./
C     ETA TOLERANCE VALUES FOR FREEWAY AND RAMP...
      DATA FTOL,RTOL /0.4 , 30.0 /
C     BULB POSITIONS VS. SENSOR LOCATIONS ON RAMP...
      INTEGER*4   GBBULB(9) / 6,16,25,30,34,43,52,61,70/
      INTEGER GBOUT(80)
      DATA KBLANK,KGEE,KVEE /' ','G','*'/
      INTEGER*2  NAMODE(4) /'IN','SM','SG','MM'/
      INTEGER*4  MASKID(2) /'MASK','UNMK'/
      INTEGER*4  NULL /'    '/
      INTEGER*4  YIELD /'YLD '/
      INTEGER*4  SLIGHT(3) / 'RED ','AMBR','GRN ' /
C     $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
      I=SENS
      J=CJ(I)
      CUTIN=.FALSE.
      OUTCUT=.FALSE.
      GOTO(30,40,10,20,50,60),CODE
C     $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
C T3, ENTRY TO LOOP 1
   10 NE(I)=NE(I)+1
      CJ(I)=1+MOD(CJ(I),JMAX)
      J=CJ(I)
      INSENS(I) = INSENS(I) + 1
      INE=NE(I)
      IF(I.EQ.7) INE = 1 + NE(I)
      IF(INSENS(I).GT.INE) INSENS(I)=INE
C RECORD A HEADWAY AT FOA/B
      IF(I.NE.47)  GO TO 101
      IF(NSENHT(54).LE.1)  GO TO 100
      TEMP = TIME - TFZERO
      NCHAN = 27
      CALL HISTGM                                                      HISTGM
  100 TFZERO = TIME
C RECORD A HEADWAY AT F1
  101 IF(I .NE. 7) GOTO 13
      IF(NSENHT(4).LE.1) GO TO 103
      TEMP = TIME - TF1
      NCHAN = 17
      CALL HISTGM                                                      HISTGM
  103 TF1 =TIME
C RECORD A HEADWAY FOR F7
   13 IF(I.NE.1)GOTO17
      IF(NSENHT(16).LE.1) GO TO 161
      TEMP=TIME-TF7
      NCHAN = 16
      CALL HISTGM                                                      HISTGM
  161 TF7 = TIME
   17 WIRE(I,J)=1
      T3(I,J)=TIME
      C(I,J)=DIST(I)
C     TEST FOR NEW VEHICLE ENTERING SYSTEM...
      IF(I.EQ.1)  GC TC 15
      ICJ=I-1
   11 IFJ=FJ(ICJ)
      IF(NE(ICJ) .EQ. 0) GOTO 620
      IF(IFJ .NE. CJ(ICJ)) GOTC 12
      IF(WIRE(ICJ,IFJ) .GE. 3) GOTC 12
      GCTC 620
   12 IF(TIME-ETA(ICJ,IFJ).LT.-FTCL)  GO TC 620
      IF(TIME-ETA(ICJ,IFJ) .GT.FTCL)  GO TC 63C
  122 STAT(I,J)=1
      CAR(I,J)=CAR(ICJ,IFJ)
      PV(I,J)=V(ICJ,IFJ)
      PT(I,J)=T3(ICJ,IFJ)
C PURGE THE FIRST VEHICLE FROM PREVIOUS SENSOR LIST
      NE(ICJ)=NE(ICJ)-1
      FJ(ICJ)=FJ(ICJ)+1
      IF(FJ(ICJ) .GT. JMAX) FJ(ICJ)=1
      GOTC 999
C CUT CUT
  630 ITEMP=CAR(ICJ,IFJ)
C PURGE THIS CAR FROM THE PREVIOUS SENSOR LIST
      NE(ICJ)=NE(ICJ)-1
      FJ(ICJ)=1+MOD(IFJ,JMAX)
      IF(I.GT.7)  GO TO 999
      IF(IXX(3).EQ.0)  WRITE(6,631)  ITEMP,SENS,TIME
      CUTCUT=.TRUE.
      COUT(I) = COUT(I) + 1.
      CALL NOISE(CUTIN,CUTOUT)                                          NCISE
C CHECK NEXT CAR IN PREVICUS SENSCR LIST
      GO TC 11
C CUT IN
  620 IF(I.GT.7)  GO TO 999
```

```
      CARNO = CARNO + 1
      CAR(I,J)=CARNO
      STAT(I,J)=2
      CUTIN=.TRUE.
      CIN(I) = CIN(I) + 1.
      IF(IXX(3).EQ.0)  WRITE(6,621)  CARNO,SENS,TIME
      GOTO 999
C LOGIC FOR VEHICLE ENTERING SYSTEM AT F7...
   15 CARNO=CARNO+1
      CAR(I,J)=CARNO
      STAT(I,J)=1
      CUTIN=.TRUE.
      IF(IXX(3).EQ.0)  WRITE(6,621)  CARNO,SENS,TIME
      CIN(I) = CIN(I) + 1.
      GOTO 999
C     $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
C T4, EXIT FROM LOOP 1
   20 IF(J.EQ.0)GOTO999
      WIRE(I,J)=1+WIRE(I,J)
      IF(WIRE(I,J) .GT. 4) GOTO 999
      T4(I,J)=TIME
      GOTO 999
C     $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
C T1, ENTRY TO LOOP 2
   30 IF(J.EQ.0)GOTO 999
      WIRE(I,J)=1+WIRE(I,J)
      IF(WIRE(I,J) .GT. 4) GOTO 999
      T1(I,J)=TIME
      TINTX=T1(I,J)-T3(I,J)
      IF(TINTX.LE.0.) GOTO 31
         V(I,J)=GAGE(I)/TINTX
      IF(I.NE.7)  GO TO 303
C     RECORD VELOCITY DISTRIBUTION AT F1...
      TEMP = V(I,J)
      NCHAN = 42
      CALL HISTGM                                                       HISTGM
  303    IF(V(I,J).GT.O. .AND. V(I,J).LT.120.) GOTO 33
C     BAD TINTX VALUE,  ASSUME A FWY SPEED...
   31 V(I,J) = 75.0
C RECCRD VELOCITY AT ALL COUBLE SENSORS
   33 VM(I)=VM(I) + V(I,J)
      VS(I)=VS(I) + V(I,J)*V(I,J)
      VC(I)=VC(I)+1.
      IF(I.GT.7)  GC TC 999
         ETA(I,J)=T3(I,J)+CS(I)  /V(I,J)
         ETANO(I,J)=T3(I,J)+DM(I)/V(I,J)
C LOAD ETA AT MERGE PCINT FOR STABILITY ANALYSIS...
      IF(CAR(I,J).EQ.C.OR.CAR(I,J).GT.1000)  GC TO 34
      XXXCUT(CAR(I,J),I) = ETANO(I,J)
   34 ACC(I,J)=0.
      IF(I.EC.1.OR.I.GT. 7 .OR. STAT(I,J).EQ.2) GOTO 999
      ACC(I,J)=(V(I,J) - PV(I,J))/ (T3(I,J) - PT(I,J) )
C HIGHWAY ACCELERATION NOISE(DCNE FOR SENSORS F7 THRU F1 ONLY)
      CALL NCISE(CUTIN,CUTCUT)                                          NCISE
      GCTC 999
C     $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
C T2, EXIT FROM LOOP 2
   40 JJ=J-1
      IF(JJ.EQ.0)JJ=JMAX
      IF(WIRE(I,JJ).LT.3)INSENS(I)=0
      IF(INSENS(I).GT.0) INSENS(I)=INSENS(I)-1
      IF(INSENS(I).EC.0)  GC TC 41
      J=JJ
   41 IF(J.EQ.0)GOTO 999
      WIRE(I,J)=1+WIRE(I,J)
      IF(WIRE(I,J) .GT. 4) GCTC 999
      IF(I.GT.7) GO TC 999
      T2(I,J)=TIME
      LEN(I,J)=(T2(I,J)-T1(I,J))*V(I,J)-6.
      IF(I.LE.7)  CALL ETACHK                                           ETACHK
      IF(I.NE.7)  GO TO 4001
C     RECORD FWY VEH LENGTH DISTRIBUTION AT F1...
      TEMP = LEN(I,J)
      NCHAN = 41
      CALL HISTGM                                                       HISTGM
C     STORE LATEST MERGE POINT ETA AT F1 FOR GAP ANALYSIS...
      CALL FMDSAV                                                       FMDSAV
C     PURGE VEHICLE FROM SENSOR F7...
      NE(I) = NE(I) - 1
C     FAKE A CUTOUT FOR PERSISTENCE ANALYSIS...
      CUTOUT = .TRUE.
      COUT(I) = COUT(I) + 1.
      IF(IXX(3).EQ.0)  WRITE(6,631)  CAR(I,J),SENS,TIME
 4001 D(I,J)=DIST(I)
      IF(IPRT1.EQ.1) CALL PRINT(1)                                      PRINT
      GOTO 999
C     $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
C TIN, ENTRY TO PRESENCE LOOP
   50 TIN(I)=TIME
      TNOC(I)=TNOC(I)+TIN(I)-TCUT(I)
C     NO TRACKING NEEDED FOR E1-E3,F1C,F1E...
C     ( ONLY COUNTS AND OCCUPANCIES DONE FOR THESE)
      IF(SENS.GT.28)  GO TO 999
      IF(IMRGPN.EQ.0)  GO TO 5000
      IF(SENS.LT.21)  GO TO 5000
      MRGOUT(MLINE) = SENS
      MRGOUT(MLINE+1) = TIME * 1000.
      MLINE = MLINE + 2
      IF(MLINE.LT.20)  GO TO 5000
      MLINE = 1
      WRITE(22,5001)  MRGOUT
 5000 IF(I.NE.10)  GO TO 155
```

```
C     LOGIC FOR CAR ENTERING RAMP AT SENSCR R10...
      CJ(I)=1+MOD(CJ(I),JMAX)
      J=CJ(I)
      VEL = 44.0
      TDIFF = TIME - TIN(9)
      IF(TCIFF.GT.0.)  VEL = 70./TCIFF
      IF(VEL.GT.50.)  VEL = 44.
      VM(I) = VM(I) + VEL
      VS(I) = VS(I) + VEL*VEL
      VC(I) = VC(I) + 1.
      CARNC = CARNC + 1
      CAR(I,J) = CARNC
C FLAG ETA CATA MATRIX TO INHIBIT READ FOR RAMP VEHICLES...
      IF(CARNO.GT.0.AND.CARNC.LT.1C01)  XXXCUT(CARNO,1) = 0.
      V(I,J) = VEL
      D(I,J) = DIST(I)
      T3(I,J) = TIME
      CUTIN = .TRUE.
      CIN(I) = CIN(I) + 1.
      IF(IXX(4).EQ.0)  WRITE(19,6C21)  CAR(I,J),SENS,TIME
C     PRCJECT ARRIVAL AT SENSCR NMBR 11 (R9) ....
      EYE = I + 1
      NE(EYE) = NE(EYE) + 1
      CJ (EYE) = 1 + MCD(CJ(EYE),JMAX)
      NJ = CJ(EYE)
      PT(EYE,NJ) = TIME
      PV(EYE,NJ) = V(I,J)
      T3(EYE,NJ) = TIME + (DIST(EYE)-DIST(I))/V(I,J)
      CAR(EYE,NJ) = CAR(I,J)
      FJ(I) = 1 + MCC(FJ(I),JMAX)
      IF(IPRT4.EQ.1) CALL PRINT(4)                                PRINT
      IF(FLAG) GO TO 125
      CAR1C = CAR(I,J)
      FLAG = .TRUE.
      WRITE(6,152)  CAR10,TIME
C STORE TIME AT R10 FOR RAMP TRAVERSE TIME
  125 KIN=KIN+1
      IF(KIN.LE.500)  RAMPT(KIN) = TIME
C RECORD A HEADWAY AT R10 - (MM)
      IF(NSENHT(31).LE.1)  GO TO 157
      TEMP=TIME-TR10
      IF(IBAFT.EQ.0)  GO TO 156
      IF(MODE.NE.3)  GO TO 156
      NCHAN = 19
      CALL HISTGM                                                       HISTGM
      GOTO 157
C RECORD A HEADWAY AT R10 - (SM OR SG)
  156 NCHAN = 21
      CALL HISTGM                                                       HISTGM
  157 TR10 = TIME
C RECORD A HEADWAY AT R1 - (MM)
  155 IF(IHIST.EQ.0) GOTO 53
      IF(I.NE.20)  GO TO 53
      IF(NSENHT(21).LE.1)  GO TO 134
      TEMP=TIME-TR1
      IF(IBAFT.EQ.0)  GO TO 133
      IF(MODE.NE.3)  GO TO 133
      NCHAN = 20
      CALL HISTGM                                                       HISTGM
      GOTO 134
C RECORD A HEADWAY FOR R1 - (SM OR SG)
  133 NCHAN = 22
      CALL HISTGM                                                       HISTGM
  134 TR1 = TIME
C GET TRAVERSE TIME FROM R10 TO R1
C NOTE...OLD KIAK10 PROCESSING IS NOW DONE IN-LINE
      IF(.NOT.FLAG)GOTO 411
      IF(CAR(I,J).LT.CAR10) GOTO 411
      KOUT=KOUT+1
      IF(KOUT.GT.500)  GO TO 411
      IF(RAMPT(KOUT).EQ.0.) GO TO 411
      TEMP = TIME - RAMPT(KOUT)
      NCHAN = 23
      CALL HISTGM                                                      HISTGM
  411 CONTINUE
C     ABORT TRACKING FOR R12 THRU R10 AT THIS POINT...
   53 IF(SENS.LT.11)  GO TO 999
C     GREEN BAND GRAPHICS OUTPUT HERE...
      IF(IBAFT.EQ.0)  GO TO 5300
      IF(I.GT.19)  GO TO 5300
      IF(KGBPIC.EQ.0)  GO TO 5300
      DO 6296 KGBX = 1,80
      GBOUT(KGBX) = KBLANK
      IF(CRDISP(KGBX*2).GT.0)  GBOUT(KGBX) = KGEE
 6296 CONTINUE
C     MARK POSITION OF SENSOR IN BAND...
      GBOUT(GBBULB(I-10)) = KVEE
      K1 = 1 + MODE
      K2 = 1 + GBMASK
      K3 = NULL
      IF(MWC.GT.0)  K3 = YIELD
      K4 = NULL
      IF(RED   .GT.0)  K4 = SLIGHT(1)
      IF(AMBER.GT.0)  K4 = SLIGHT(2)
      IF(GREEN.GT.0)  K4 = SLIGHT(3)
      WRITE(21,6297)  TBAND,SENS,TIME,GBOUT,NAMODE(K1),MASKID(K2),
     *                K3,K4,VMRG,VBAR,Q
 5300 IF(NE(I).EQ.0) GOTO 56
      MMAX=NE(I)
      DO 51 M=1,MMAX
      J=FJ(I)
      IF(TIME-T3(I,J).LT.-RTOL)  GO TO 56
      IF(TIME-T3(I,J) .LT.RTOL)  GC TO 54
C THIS IS A CUTCUT, PLRGE TCP CAR CF SENSCR I
  5CO NE(I)=NE(I)-1
      COUT(I) = COUT(I) + 1.
      FJ(I)=1+MOD(FJ(I),JMAX)
C     CALL CN MERGE RCUTINE TC SEARCH FCR GAPS...
C     IF(I.GT.20.AND.I.LT.29)  CALL MERGE                            MERGE
C     CONSIDER REJECTEC GAP PCSSIBILITY FOR THIS VEHICLE...
C     IF(I.GT.20.AND.I.LT.29)  CALL REJGAP                           REJGAP
      IF(I.EC.28)  GO TO 51
      D(I,J)=DIST(I)
      CUTOUT=.TRUE.
      IF(IXX(4).EQ.0)  WRITE(19,6C31)  CAR(I,J),SENS,TIME
      CUTCUT=.FALSE.
   51 CONTINUE
      GOTC 999
C CUTIN AT PCSITION SENSORS
   56 D(I,J)=DIST(I)
      CUTIN = .TRUE.
      CIN(I) = CIN(I) + 1.
      IF(IXX(4).EQ.0)  WRITE(19,6021)  CAR(I,J),SENS,TIME
      GCTC 999
C THIS IS AN ICENTIFIEC EVENT
   54 T3(I,J)=TIME
      V(I,J)=(CIST(I)-CIST(I-1))/(T3(I,J)-PT(I,J))
C     CC RAMP VEH/ FREEWAY GAP MATCH PRCJECTION...
      IF(I.EQ.20)  CALL FGPMR1                                       FGPMR1
      VM(I)=VM(I) + V(I,J)
      VS(I)=VS(I) + V(I,J)*V(I,J)
      VC(I)=VC(I)+1.
      ACC(I,J) = 0.0
      IF(I.EQ.10)  GO TO 540
      ACC(I,J)=(V(I,J) - PV(I,J))/ (T3(I,J) - PT(I,J) )
      IF(ABS(ACC(I,J)).GT.20.)  ACC(I,J) = 0.
      IF(IBAFT.EQ.1)  GO TO 538
C     THIS IS A BEFORE STUDY...
      IF(I.LT.21)  CALL RNOISE                                            RNOISE
      IF(ACC(I,J).LT.-8.0)  KRCNFL(I-10) = KRCNFL(I-10) + 1
      GO TO 540
  538 IF(I.LT.21.AND.MODE.EQ.3)  CALL RNOISE                              RNOISE
C     CHECK CONFLICT DUE TO XS SPEED CHANGE BY RAMP VEHICLE...
C     (DO NOT COUNT VEHICLES STOPPING FOR LIGHT)
      IF(I.LE.14.AND.MODE.NE.3)  GO TO 540
      IF(ACC(I,J).LT.-8.0)  KRCNFL(I-10) = KRCNFL(I-10) + 1
  540 D(I,J)=DIST(I)
C     ACCUMULATE GB DATA, IF REQUESTED...
      IF(IBAFT.EQ.0)  GO TO 401
      IF(I.GT.19)  GO TO 401
C RED LIGHT VIOLATIONS IN THE SM AND SG MODES...
      IF(I.EQ.15.AND.MODE.EQ.1.AND.RED.EQ.1)  KSMRED = KSMRED + 1
      IF(I.EQ.15.AND.MODE.EQ.2.AND.RED.EQ.1)  KSGRED = KSGRED + 1
C BAND TRACKING ANALYSIS...
      IF((MODE.EQ.3.AND.I.GE.11).OR.(MODE.EQ.2.AND.I.GE.15))CALL GRBAND GRBAND
C RAMP VEHICLE ACTIVITY AT THE YIELD SIGN...
      IF(I.NE.18)  GO TO 401
      IF(MODE-2)  401,402,403
  402 IF(GBMASK.EQ.1)  GO TO 4020
      N3SGM = N3SGM + 1
      GO TO 401
 4020 N3SGUM = N3SGUM + 1
      N3SGYL = N3SGYL + MWC
      GO TO 401
  403 IF(GBMASK.EQ.1)  GO TO 4030
      N3MMM = N3MMM + 1
      GO TO 401
 4030 N3MMUM = N3MMUM + 1
      N3MMYL = N3MMYL + MWC
  401 IF(I.EQ.28)  GO TO 58
```

```
C EXTRAPOLATE THE NEXT EVENT
      EYE=I+1
      CJ(EYE)=1+MOD(CJ(EYE),JMAX)
      NJ=CJ(EYE)
      NE(EYE)=NE(EYE)+1
      T3(EYE,NJ)=T3(I,J)+(DIST(EYE)-DIST(I))/V(I,J)
      PV(EYE,NJ) = V(I,J)
      PT(EYE,NJ)=T3(I,J)
      CAR(EYE,NJ)=CAR(I,J)
C PURGE FROM THIS SENSOR LIST
   58 NE(I)=NE(I)-1
      FJ(I)=1+MOD(FJ(I),JMAX)
      IF(IPRT4.EQ.1) CALL PRINT(4)                                   PRINT
      IF(I.EQ.28)  NE(I) = 0
      GOTO 999
C     $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
C TOUT, EXIT FROM PRESENCE LOOP
   60 TOUT(I)=TIME
      TOC(I)=TOC(I)+TOUT(I)-TIN(I)
      IF(I.GT.9)  GO TO 999
C     DO APPROXIMATE VELOCITY ESTIMATES AT R12,R11...
      TDIFF = TOUT(I) - TIN(I)
      VEL = 44.0
      IF(TDIFF.GT.0.0)  VEL = 18./TDIFF
      VM(I) = VM(I) + VEL
      VS(I) = VS(I) + VEL*VEL
      VC(I) = VC(I) + 1.
      GOTO 999
C     $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
  999 CONTINUE
      RETURN
  152 FORMAT(' 1ST VEH AT R10 = ',I4,', AT TIME = ',F10.3)
  621 FORMAT(1X,11HCUTIN,  CAR,2I5,F10.3)
  631 FORMAT(1X, 11HCUTOUT, CAR, 2I5,F10.3)
```

```
5001 FORMAT(10(I2,I6))
6021 FORMAT(90X,'CUTIN ',2I6,F10.3)
6031 FORMAT(90X,'CUTOUT',2I6,F10.3)
6297 FORMAT(1X,F9.3,I3,F9.3,1X,80A1,1X,A2,1X,A4,1X,2A4,3I4)
     END
```

```
      SUBROUTINE TREAD
C
C     TREAD IS CALLED BY EVENT TO READ THE DATA TAPES GENERATED
C     ON-LINE BY THE GB SYSTEM.  ITS OUTPUT IS AN ARRAY OF SIZE (8,3000)
C     WHICH CONTAINS BIT PATTERNS FROM THE TAPE.
C
      COMMON /NDATA/N,DATA
      INTEGER*4 IUNIT,IWORD
      INTEGER*2 DATA(24000),EIJP1,ITAPE(3000),A,TEST
      LOGICAL*1 T,L(2),Z
      DATA Z/Z00/,T/ZFF/,TEST/Z00FF/
      EQUIVALENCE (L(1),A)
C     LOGICAL UNIT NUMBER FOR TAPE INPUT DEVICE...
      DATA  IUNIT/9/
      N=0
      ERR=1
200   CONTINUE
      L(1)=Z
      L(2)=T
      DO 5 J=1,3000
5     ITAPE(J)=A
    1 READ(IUNIT,11,END=99,ERR=500) (ITAPE(K),K=1,3000)
11    FORMAT(30(100A1))
   20 DO 6 J=1,3000
       EIJP1=8*J+1
      A=ITAPE(J)
      IF(A.EQ.TEST) GO TO 41
      L(2)=L(1)
      L(1)=Z
      IWORD=A
      DO 7 LL=1,8
      DATA(EIJP1-LL)=MOD(IWORD,2)
    7 IWORD=IWORD/2
      N=N+1
    6 CCNTINUE
41      N=N*ERR
        RETURN
500     ERR=-1
        GO TC 200
   99 N=0
        RETURN
        END
```

```
      SUBROUTINE XDDSP(DATA,CLOCK,KXSDIS)
C
C     XDDSP IS CALLED BY EVENT TO PROCESS AND RECORD TAPE DATA
C     REPRESENTING FIELD ACTIVITY(E.G., THE DISPLAY BULBS AND SIGNS).
C
      COMMON/EVENTS/ ETABLE(1000,3),IETROW
      COMMON/FIELD/DRDISP,DBGB,PTS,RED,AMBER,GREEN,
     1             VMRG,VBAR,G,MWC,MODE,GBMASK
      INTEGER*4  KDISC /20/
      INTEGER*2  DRDISP(160),DBGB,PTS,RED,AMBER,GREEN,
     1             VMRG,VBAR,G,MWC,MODE,GBMASK,DATA(8,74),WORD(16)
      NGO = 3
      NLFTB = 1
      NRTB = 2
      KXSDIS = 0
      DO 382 I = 1,8
      DO 382 I8P1 = 1,20
      I8 = I8P1 - 1
      ISUB = I8 * 8
  382 DRDISP(I+ISUB) = DATA(I,NGO+I8)
      NLFTB = NLFTB + 22
      NRTB = NRTB + 22
      DO 383 J=1,8
      WORD(J) = DATA(J,NLFTB)
  383 WORD(J+8) = DATA(J,NRTB)
        MWC = WORD(1)
        DBGB = WORD(6)
        PTS = WORD(7)
        RED = WORD(10)
        AMBER = WORD(11)
        GREEN = WORD(12)
      NLFTB = NLFTB + 2
      NRTB = NRTB + 2
      DO 384 J = 1,8
```

```
    WORD(J) = DATA(J,NLFTB)
384 WORD(J+8) = DATA(J,NRTB)
       MODE = 2*WORD(15) + WORD(16)
    NLFTB = NLFTB + 2
    NRTB = NRTB + 2
    DO 385 J = 1,8
    WORD(J) = DATA(J,NLFTB)
385 WORD(J+8) = DATA(J,NRTB)
    VMRG = 0
    DO 386 JSUM = 9,16
386 VMRG   = VMRG    + WORD(JSUM)*(2**(16-JSUM))
    VBAR = 0
    DO 387 JSUM = 1,8
387 VBAR = VBAR + WORD(JSUM)*(2**(8-JSUM))
    NLFTB = NLFTB + 2
    NRTB = NRTB + 2
    DO 388 J = 1,8
    WORD(J) = DATA(J,NLFTB)
388 WORD(J+8) = DATA(J,NRTB)
    Q = 0
    DO 389 JQ = 9,16
389 Q = Q + WORD(JQ)*(2**(16-JQ))
    GBMASK = WORD(8)
    WRITE(KDISC) DRDISP,DBGB,PTS,RED,AMBER,GREEN,
   1             VMRG,VBAR,Q,MWC,MODE,GBMASK
    IETROW = IETROW + 1
    IF(IETROW.GT.1000)  GO TO 500
    ETABLE(IETROW,1) = 65.
    ETABLE(IETROW,2) = 1.0
    ETABLE(IETROW,3) = CLOCK
    RETURN
500 KXSDIS = 1
    RETURN
    END
```

```
      SUBROUTINE XLABEL(DATA,CLOCK)
C
C     XLABEL IS CALLED BY EVENT TO DECODE AND PRINT THE TELETYPE
C     MESSAGES ENTERED BY THE GB SYSTEM OPERATOR WHEN DATA LOGGING
C     IS ACTIVE.
C
      INTEGER*4 P /16/
      INTEGER*2 DATA(8,74),CHAR(64),MSG(72)
      DATA IBLANK /' '/
C     FOLLOWING IS TABLE OF ASCII CODES FOR TELETYPE MESSAGES...
C     (REFERENCE... PAGE 5.40 OF RAYTHEON 704 USER'S MANUAL)
      DATA CHAR/4*' ','$',' ','+',1H','(',')','*','+',',','-','.','/',
     1'0','1','2','3','4','5','6','7','8','9',' ',' ',' ','=',' ',' ',
     2' ','A','B','C','D','E','F','G','H','I','J','K','L','M','N','O',
     3'P','Q','R','S','T','U','V','W','X','Y','Z',5*' '/
      DO 254 JCLEAR=1,72
  254 MSG(JCLEAR)=IBLANK
      NCHAR = 1
      DO 255 ISCAN=3,74
      NVAL=0
      DO 260 J=2,8
  260 NVAL=NVAL+DATA(J,ISCAN)*2**(8-J)
      IF(NVAL.EQ.13)  GO TO 256
      IF(NVAL.LT.32.OR.NVAL.GT.95) NVAL=32
      MSG(NCHAR)=CHAR(NVAL-31)
      NCHAR=NCHAR+1
  255 CONTINUE
  256 WRITE (P,1010) CLOCK,MSG
 1010 FORMAT(1X,72('-'),/,1X,'AT CLOCK = ',F10.3,', THE FOLLOWING TELETY
     *PE MESSAGE WAS WRITTEN...',/,1X,72A1,/,1X,72('-'),/)
      RETURN
      END
```

APPENDIX B

FORTRAN LISTING OF THE GREEN BAND ON-LINE CONTROL PROGRAM SIMULATION ROUTINES

```
C     SIMULATED GREEN BAND EXCUTIVE ROUTINE
C
C     ISR  CALLED 500 TIMES/SEC
C     HVP  CALLED 100 TIMES/SEC, 1ST CALL ON SECOND INTERRUPT
C     GBS  CALLED 100 TIMES/SEC, 1ST CALL ON THIRD INTERRUPT
C     GBUD CALLED 100 TIMES/SEC, 1ST CALL ON FOURTH INTERRUPT
C
      COMMON/GBT/NBANDS,TBAND(15),VBAND(15),XLE(15),XTE(15),
     *           BT1(15),BT2(15),ALLG,VMRG
      COMMON/OCNTRL/  IOUT
      COMMON/RUN/ TSTART,TSTOP
      COMMON/SFLAG/  ACTF(7)
      COMMON/TIMER/ICLOCK,TIME,TNEXT
C
C     FOLLOWING VARIABLE CONTROLS DETAILED OUTPUT OPTION...
      IOUT = 0
      IOUT = 1
C
C     ESTABLISH RUN TIME CONDITIONS...
      TSTART = 0.850
      TSTOP = 20.
C
C     INITIALIZE TIME VARIABLES
      TIME = TSTART
      ICLOCK = TIME*500.
C
C     INITIALZE VARIABLES FOR ISR AND GBUD ROUTINES...
      NBANDS = 0
      ALLG = 0.
      VMRG = 66.
C
      CALL ISRINI
      CALL HVPINI
C
```

```
C     SET UP CALLING SEQUENCE COUNTERS FOR SUBROUTINES
      NHVP = 3
      NGBS = 2
      NGBUD = 1
C
C     MAIN PROCESSING SEQUENCE...
  100 CALL ISR
C
      NHVP = NHVP +1
      IF(NHVP.EQ.5)  CALL HVP
      IF(NHVP.EQ.5)  NHVP = 0
C
      NGBS = NGBS + 1
      IF(NGBS.EQ.5)  CALL GBS
      IF(NGBS.EQ.5)  NGBS = 0
C
      NGBUD = NGBUD + 1
      IF(NGBUD.EQ.5)  CALL GBUD
      IF(NGBUD.EQ.5)  NGBUD = 0
C
C     UPDATE CLOCK (COUNT OF 2 MILLISECOND INTERRUPT CYCLES)
      ICLOCK = ICLOCK + 1
      CLOCK = ICLOCK
      TIME = CLOCK/500.0
      IF(TIME.LT.TSTOP)  GO TO 100
      STOP
      END
      SUBROUTINE ISRINI
      COMMON/INPUT/  RAWDAT(7,100,5),STNEXT(7),INEXT(7)
      COMMON/NEXT/ISENS,T1,ICAR,VEL,XLEN,ETA
      COMMON/RUN/ TSTART,TSTOP
      COMMON/SFLAG/  ACTF(7)
      COMMON/TIMER/ICLOCK,TIME,TNEXT
      DIMENSION INSENS(7)
C
C     CLEAR VEHICLE COUNTERS FOR INPUT ARRAY...
      DO 1 I = 1,7
    1 INSENS(I) = 0
C
C     BRING IN ENOUGH FREEWAY DATA FROM CARDS TO SATISFY RUN TIMING
C     PARAMETERS ESTABLISHED IN MAIN...
C
    2 READ(5,200) ISENS,T2,ICAR,VEL,XLEN,ETA
  200 FORMAT(9X,I1,F12.0,I12,3F12.0)
C     TIME READ IS T2, ADJUST TO T1 VALUE...
      T1 = T2 - (XLEN+6.)/VEL
C     CONVERT VEHICLE LENGTH IN FEET TO LENGTH IN TIME...
      XLEN = XLEN/VEL
      WRITE(6,101) TIME,ISENS,T1,ICAR,VEL,XLEN,ETA
  101 FORMAT(  1X,'TIME=',F9.3,',ISRINI READING...',I3,F9.3,I4,3F9.3)
C
C
C     COUNT NUMBER OF VEHICLES READ AT EACH SENSOR STATION...
      INSENS(ISENS) = INSENS(ISENS) + 1
      IF(INSENS(ISENS).GT.100)  STOP
C
C     LOAD RAW DATA ARRAY FROM PUNCHED TOGAP OUTPUT...
        RAWDAT(8-ISENS,INSENS(ISENS),1) = ETA
        RAWDAT(8-ISENS,INSENS(ISENS),2) = T1
        RAWDAT(8-ISENS,INSENS(ISENS),3) = VEL
        RAWDAT(8-ISENS,INSENS(ISENS),4) = XLEN
        RAWDAT(8-ISENS,INSENS(ISENS),5) = ICAR
C
      IF(T1.LT.(TSTOP+15.))  GO TO 2
C
C     DATA IS READY, SET UP RUN CONTROL FLAGS AND TIMERS...
      DO 10 I = 1,7
      STNEXT(I) = RAWDAT(I,1,2)
   10 INEXT(I) = 1
C
C     TURN OFF 'SENSOR DATA READY' FLAGS FOR HVP...
      DO 50 I = 1,7
   50 ACTF(I) = +1.0
C
      RETURN
      END
      SUBROUTINE ISR
      COMMON/INPUT/  RAWDAT(7,100,5),STNEXT(7),INEXT(7)
      COMMON/NEXT/ISENS,T1,ICAR,VEL,XLEN,ETA
      COMMON/SFLAG/  ACTF(7)
      COMMON/TIMER/ICLOCK,TIME,TNEXT
C
C     THIS SUBROUTINE SIMULATES THE SCANNING OF FIELD SENSOR DATA
C     IN THE ON-LINE SYSTEM BY USING HISTORICAL DATA OBTAINED FROM
C     REDUCED DATA GENERATED BY THE TOGAP SYSTEM.
C
C     NOTE...THE PROGRAM DOES NOT LOOK AHEAD IN TIME.
C     THE VARIABLE TNEXT INDICATES WHEN THE NEXT FIELD SENSOR
C     DATA WILL BE READY.  UNTIL THAT TIME, ISR REPORTS NO NEW DATA.
C
C     SCAN SENSORS, TURN ON 'DATA READY' FLAGS IF APPROPRIATE...
      DO 1000 I = 1,7
      IF(TIME.GE.STNEXT(I))  ACTF(I) = -1.0
 1000 CONTINUE
C
C     SEARCH FOR SMALLEST OF THE NEXT SENSOR ACTIVATION TIMES...
C     NOTE... THIS VALUE IS NOT CURRENTLY USED IN THE SIMULATION,
C     BUT COULD BE USED IN A SIMULATION STRATEGY BASED ON EVENT
C     SCANNING RATHER THAN THE CURRENT MODE OF TIME SCANNING.
C
      TNEXT = 1.0E60
      DD 2000 I = 1,7
      IF(STNEXT(I).LT.TNEXT) TNEXT=STNEXT(I)
 2000 CONTINUE
C
      RETURN
      END
      SUBROUTINE HVPINI
      COMMON/BINS/  SETA(9,7),ST1(9,7),SVEL(9,7),SLEN(9,7),
     *              SNC(9,7),NLIST(7)
      COMMON/FWYDAT/NVEH,FETA(63),FT1(63),FVEL(63),FXLEN(63),NC(63)
C
C     THIS ROUTINE CLEARS THE HIGHWAY VEHICLE DATA LIST COUNTS TO
C     ZERO VALUES TO SET UP THE INITIAL HIGHWAY VEHICLE PROCESSING
C     CONDITIONS.
C
      DO 50 I = 1,7
   50 NLIST(I) = 0
C
      NVEH = 0
C
      RETURN
      END
      SUBROUTINE HVP
      COMMON/BINS/  SETA(9,7),ST1(9,7),SVEL(9,7),SLEN(9,7),
     *              SNC(9,7),NLIST(7)
      COMMON/FWYDAT/NVEH,FETA(63),FT1(63),FVEL(63),FXLEN(63),NC(63)
      COMMON/NEXT/ISENS,T1,ICAR,VEL,XLEN,ETA
      COMMON/OCNTRL/  IOUT
      COMMON/SFLAG/  ACTF(7)
      COMMON/TIMER/ICLOCK,TIME,TNEXT
C
C     NOTE... THOLD CONTROLS FWY VEHICLE RETENTION TIME IN DATA TABLES...
      DATA THOLD / 3.0 /
C
C     THIS ROUTINE SIMULATES THE ACTIONS OF THE HVP ROUTINE IN
C     THE ON-LINE GREEN BAND CONTROL PROGRAM.   NOTE THAT THE
C     VARIABLES IT USES TO UPDATE THE FREEWAY LISTS ARE ALREADY
C     COMPUTED AND SUPPLIED BY ISR.  IN THE ON-LINE SYSTEM, THESE
C     VALUES MUST BE COMPUTED BY THE HVP FROM SENSOR EVENT TIME DATA.
C
C     PROCESS CURRENT FWY DATA LISTS TO REMOVE ANY VEHICLES
C     PAST DUE AT THE MERGE POINT...
C
      DO 200 ILIST = 1,7
      JNV = NLIST(ILIST)
      IF(JNV.EQ.0) GO TO 200
      NSQ = 0
      DO 100 JVEH = 1,JNV
C     MARK OVERTIME VEHICLES WITH NEGATIVE ETA VALUE...
      IF(SETA(JVEH,ILIST).GE.TIME)  GO TO 100
         SETA(JVEH,ILIST) = -99.
         NSQ = NSQ + 1
  100 CONTINUE
C     ROUTINE 'SQUEZE' REMOVES ALL VEHICLES IN CURRENT LIST WITH
C     NEGATIVE ETA VALUES...
      IF(NSQ.GT.0)  CALL SQUEZE(ILIST)
  200 CONTINUE
C
C     DO LIST SCAN FOR NEW DATA UPDATES...
      DO 400 I = 1,7
C
C     IS THERE NEW DATA READY FOR THIS LIST
      IF(ACTF(I).GE.0.) GO TO 400
C
C     DATA IS AVAILABLE FOR LIST I, IS THE LIST CURRENTLY EMPTY
  401 IF(NLIST(I).GT.0)  GO TO 405
C
C     THE CURRENT LIST IS EMPTY, SO INSERT THE NEW DATA AND CONTINUE
C     PROCESSING WITH THE NEXT LIST...
      CALL INSERT(I)
      GO TO 400
C
C     THE CURRENT LIST HAS AT LEAST ONE ENTRY.
C
C     CHECK VEHICLE RETENTION TIME FOR THE TOP VEHICLE IN LIST
C     (E.G., IS THE VEHICLE OVERDUE AT THE NEXT DOWNSTREAM SENSOR )
C
  405 IF((ST1(1,I)+THOLD).GT.TIME)  GO TO 410
C
C     FIRST VEHICLE IS OVERDUE, DELETE IT AND PUSH LIST UP...
      SETA(1,I) = -99.
      CALL SQUEZE(I)
C     PUT NEW DATA IN UPDATED LIST...
      CALL INSERT(I)
C
C     FIRST VEHICLE IN THE LIST IS NOT OVERDUE, CHECK TO SEE IF THE LIST
C     IS FULL...
  410 IF(NLIST(I).EQ.9)  GO TO 420
C
C     LIST IS NOT FULL, STORE THE NEW DATA...
```

```
      CALL INSERT(I)
      GO TO 400
C
C     LIST IS NOW FULL, DELETE FIRST VEHICLE...
  420 SETA(1,I) = -99.
      CALL SQUEZE(I)
C     LIST NOW HAS 8 ENTRIES, STORE THE NEW DATA IN THE LAST POSITION...
      CALL INSERT(I)
  400 CONTINUE
C
C     NOW FINISHED WITH INDIVIDUAL SENSOR LIST PROCESSING, SO COPY
C     THE INDIVIDUAL SENSOR BINS INTO THE MASTER ARRAY USED BY THE SIMULATED
C     GBS ROUTINE...
      IGO = 1
      DO 500 ILIST = 1,7
      NV = NLIST(ILIST)
      IF(NV.EQ.0)  GO TO 500
      DO 501 ICOPY = 1,NV
         FETA(IGO) = SETA(ICOPY,ILIST)
         FT1 (IGO) = ST1 (ICOPY,ILIST)
         FVEL(IGO) = SVEL(ICOPY,ILIST)
         FXLEN(IGO)= SLEN(ICOPY,ILIST)
         NC  (IGO) = SNC(ICOPY,ILIST)
         IGO = IGO + 1
  501 CONTINUE
  500 CONTINUE
C
C     COMPUTE NUMBER OF VEHICLES IN CURRENT LIST...
      NVEH = IGO - 1
      IF(IOUT.EQ.1)  CALL BINOUT(1)
      RETURN
      END
      SUBROUTINE INSERT(ILIST)
      COMMON/BINS/  SETA(9,7),ST1(9,7),SVEL(9,7),SLEN(9,7),
     *              SNC(9,7),NLIST(7)
      COMMON/INPUT/  RAWDAT(7,100,5),STNEXT(7),INEXT(7)
      COMMON/NEXT/ISENS,T1,ICAR,VEL,XLEN,ETA
      COMMON/SFLAG/  ACTF(7)
      DATA HMIN/0.8/
C
C     THIS ROUTINE PLACES NEW FREEWAY VEHICLE DATA IN THE CURRENT DATA
C     LIST REPRESENTING THE SENSOR 'BIN' AT LOCATION ILIST IN THE ON-LINE
C     PROGRAM.
C
C     IF CURRENT LIST EMPTY, GO TO SIMPLE INSERTION CASE...
      IF(NLIST(ILIST).EQ.0)  GO TO 200
C
C     CURRENT LIST IS NOT EMPTY, PUT NEW DATA AT END...
  100 SETA(NLIST(ILIST)+1,ILIST) = RAWDAT(ILIST,INEXT(ILIST),1)
      ST1 (NLIST(ILIST)+1,ILIST) = RAWDAT(ILIST,INEXT(ILIST),2)
      SVEL(NLIST(ILIST)+1,ILIST) = RAWDAT(ILIST,INEXT(ILIST),3)
      SLEN(NLIST(ILIST)+1,ILIST) = RAWDAT(ILIST,INEXT(ILIST),4)
      SNC (NLIST(ILIST)+1,ILIST) = RAWDAT(ILIST,INEXT(ILIST),5)
C
C     NOW DO MINIMUM FWY VEHICLE ETA TEST ... E.G., IF COMPUTED MP ETA
C     IS LESS THAN THAT OF THE PREVIOUS VEHICLE, SET THE NEW ETA EQUAL
C     TO THE OLD VALUE + HMIN.
C
      IF(SETA(NLIST(ILIST)+1,ILIST).LT.SETA(NLIST(ILIST),ILIST))
     *     SETA(NLIST(ILIST)+1,ILIST) = SETA(NLIST(ILIST),ILIST) + HMIN
C     BUMP LIST COUNT...
      NLIST(ILIST) = NLIST(ILIST) + 1
      GO TO 2000
C
C     LIST WAS EMPTY, INSERT NEW DATA AT FIRST POSITION...
  200 SETA(1,ILIST) = RAWDAT(ILIST,INEXT(ILIST),1)
```

```
      ST1 (1,ILIST) = RAWDAT(ILIST,INEXT(ILIST),2)
      SVEL(1,ILIST) = RAWDAT(ILIST,INEXT(ILIST),3)
      SLEN(1,ILIST) = RAWDAT(ILIST,INEXT(ILIST),4)
      SNC (1,ILIST) = RAWDAT(ILIST,INEXT(ILIST),5)
C
C     ADJUST LIST COUNT TO REFLECT SINGLE ENTRY...
      NLIST(ILIST) = 1
C
C     TURN OFF 'SENSOR ACTIVE' FLAG AND UPDATE POINTER VARIABLES TO
C     FUTURE SENSOR ACTIVATIONS ON THE CHANNEL...
C
 2000 ACTF(ILIST) = +1.0
      INEXT(ILIST) = INEXT(ILIST) + 1
      STNEXT(ILIST) = RAWDAT(ILIST,INEXT(ILIST),2)
C
      RETURN
      END
      SUBROUTINE SQUEZE(ILIST)
      COMMON/BINS/  SETA(9,7),ST1(9,7),SVEL(9,7),SLEN(9,7),
     *              SNC(9,7),NLIST(7)
C
C     THIS ROUTINE COMPRESSES FREEWAY DATA LISTS BY MOVING TABLE
C     ENTRIES UP IN THE SPECIFIED LIST TO REPLACE SENSOR REPORTS
C     MARKED AS UNACCEPTABLE BY THE HVP.
C
C     THE 'DATA UNACCEPTABLE' CONDITION FOR THE SIMULATION SCHEME IS
C     INDICATED BY A NEGATIVE VALUE FOR A VEHICLE ETA SET BY HVP.
C
      IF(NLIST(ILIST).GT.1)  GO TO 200
C
C     LIST HAD ONLY ONE ELEMENT, DELETE BY ZEROING COUNT.
      NLIST(ILIST) = 0
      RETURN
C
C     FIND FIRST NEGATIVE ETA IN CURRENT LIST...
  200 NNLIST = NLIST(ILIST)
      DO 205 IBAD = 1,NNLIST
      IF(SETA(IBAD,ILIST).LT.0.)  GO TO 207
  205 CONTINUE
C
C     LIST IS NOW O.K., RETURN TO HVP...
      RETURN
C
C     SQUEEZE LIST UP FROM BAD DATA ROW...
  207 IF(IBAD.EQ.NNLIST)  GO TO 209
      INM1 = NNLIST - 1
      DO 208 IMOVE = IBAD,INM1
         SETA(IMOVE,ILIST) = SETA(IMDVE+1,ILIST)
         ST1 (IMOVE,ILIST) = ST1 (IMDVE+1,ILIST)
         SVEL(IMOVE,ILIST) = SVEL(IMDVE+1,ILIST)
         SLEN(IMOVE,ILIST) = SLEN(IMDVE+1,ILIST)
```

```
        SNC (IMOVE,ILIST) = SNC (IMOVE+1,ILIST)
  208 CONTINUE
      NLIST(ILIST) = NLIST(ILIST) - 1
      IF(NLIST(ILIST).EQ.0)  RETURN
      GO TO 200
  209 NLIST(ILIST) = NLIST(ILIST) - 1
      RETURN
      END
      SUBROUTINE BINOUT(IOPT)
      COMMON/BINS/  SETA(9,7),ST1(9,7),SVEL(9,7),SLEN(9,7),
     *              SNC(9,7),NLIST(7)
      COMMON/FWYDAT/NVEH,FETA(63),FT1(63),FVEL(63),FXLEN(63),NC(63)
      COMMON/TIMER/ICLOCK,TIME,TNEXT
C
C     THIS ROUTINE PRINTS THE CURRENT CONTENTS OF THE SEVEN HIGHWAY
C     VEHICLE DATA BINS IN THE SIMULATED HVP ROUTINE.
C
      IF(IOPT.EQ.1)  WRITE(6,10)  TIME,NVEH
   10 FORMAT(/  ,' HVP FINISHED AT TIME = ',F9.3,', WITH NVEH = ',I4)
C
      DO 100 IS = 1,7
      WRITE(6,90)  IS,IS,NLIST(IS)
   90 FORMAT(1X,'SENSOR BIN ',I2,'... NLIST(',I2,')=',I2)
      IF(NLIST(IS).EQ.0)  GO TO 100
      NV = NLIST(IS)
      DO 95 JV = 1,NV
   95 WRITE(6,96)  JV,SETA(JV,IS),ST1(JV,IS),SVEL(JV,IS),
     *             SLEN(JV,IS),SNC(JV,IS)
   96 FORMAT(1X,'VEH. NO. = ',I2,', ETA,T1,VEL,LEN,CARID=',4F10.3,F5.0)
  100 CONTINUE
      RETURN
      END
      SUBROUTINE GBS
      COMMON/BINS/  SETA(9,7),ST1(9,7),SVEL(9,7),SLEN(9,7),
     *              SNC(9,7),NLIST(7)
      COMMON/FWYDAT/NVEH,FETA(63),FT1(63),FVEL(63),FXLEN(63),NC(63)
      COMMON/GBT/NBANDS,TBAND(15),VBAND(15),XLE(15),XTE(15),
     *           BT1(15),BT2(15),ALLG,VMRG
      COMMON/OCNTRL/  IOUT
      COMMON/TIMER/ICLOCK,TIME,TNEXT
      REAL*4  THDY,LHDY
      DATA THDY,LHDY /1.2,0.4/
      DATA ZERO /0.0/
C
C     THIS ROUTINE SIMULATES THE GBS ROUTINE OF THE ON-LINE CONTROL
C     SYSTEM.  FREEWAY VEHICLE DATA IS SEARCHED FOR ACCEPTABLE
C     GAPS.  BANDS REPRESENTING THESE GAPS ARE CREATED FOR OUTPUT BY
C     THE GBUD ROUTINE.
C
C     PRINT FREEWAY VEHICLE DATA TABLES...
      IF(IOUT.EQ.0)  GO TO 8891
      WRITE(6,8888)  TIME,NVEH,NLIST
 8888 FORMAT(  1X,'TIME=',F9.3,', NVEH = ',I3,', NLIST= ',7I5)
      IF(NVEH.EQ.0)  GO TO 8891
      DO 8889 IV = 1,NVEH
 8889 WRITE(6,8890)  IV,FETA(IV),FT1(IV),FVEL(IV),FXLEN(IV),NC(IV)
 8890 FORMAT(1X,'FWY VEH NO. ',I2,' ...',4F12.3,I5)
 8891 CONTINUE
C     ABORT THE RUN IF DATA TABLES ARE OVERFLOWING...
      IF(NVEH.GT.63)  STOP
C
C     TEST FOR UPSTREAM SECTION 'ALL CLEAR' CONDITION...
      IF(NVEH.GT.0)  GO TO 100
      ALLG = 1.
      RETURN
C
```

```
C     SET BAND COUNTER TO ZERO, CREATE NEW SET...
  100 NBANDS = 0
C     TURN OFF ALL GREEN FLAG TO INDICATE THERE ARE ACTIVE BANDS...
      ALLG = 0.
C
C     CREATE FIRST BAND
      NL = 1
      NT = 1
      NBANDS = NBANDS + 1
      XLE(NBANDS) = 844.
      CALL XLTE(FETA(1),ZERO,THDY,VBAND(NBANDS),XTE(NBANDS))
      TBAND(NBANDS) = TIME
      BT1(NBANDS) = -1.
      BT2(NBANDS) = FETA(1)
      IF(NVEH.EQ.1)  GO TO 300
C
C     DO INTERMEDIATE BAND PROCESSING...
  200 NT = NT + 1
      IF(NT.GT.NVEH)  GO TO 300
      IF(FETA(NT).LE.(FETA(NL)+0.25))  GO TO 200
C     CHECK FOR MIN ETA SPACING OF 2 SECONDS
      IF(FETA(NT).GT.(FETA(NL)+2.0))  GO TO 250
      NL = NT
      GO TO 200
C     COMPUTE MEASURED GAP
  250 XMGAP = FETA(NT) - FETA(NL) - FXLEN(NL)
C     COMPUTE REQUIRED GAP
      CALL RAYGAP(NT,NL,RGAP)
      IF(IOUT.EQ.1)  WRITE(6,2000)  TIME,NT,NL,XMGAP,RGAP
 2000 FORMAT(  1X,'TIME=',F9.3,', TVEH,LVEH,MGAP,RGAP...',2I3,2F12.3)
C     IS THIS GAP ADEQUATE
      IF(XMGAP.GE.RGAP)  GO TO 275
      NL = NT
      GO TO 200
```

```
C
C      YES, CREATE NEW BAND...
  275 NBANDS = NBANDS + 1
      CALL XLTE(FETA(NL),FXLEN(NL),LHDY,VBAND(NBANDS),XLE(NBANDS))
      CALL XLTE(FETA(NT),ZERO,THDY,VDUMMY,XTE(NBANDS))
      TBAND(NBANDS) = TIME
      BT1(NBANDS) = FETA(NL)
      BT2(NBANDS) = FETA(NT)
      NL = NT
      GO TO 200
C
C      DO PROCESSING FOR LAST BAND
  300 NBANDS = NBANDS +1
      CALL XLTE(FETA(NVEH),FXLEN(NVEH),LHDY,VBAND(NBANDS),XLE(NBANDS))
      XTE(NBANDS) = -9999.
      TBAND(NBANDS) = TIME
      BT1(NBANDS) = FETA(NVEH)
      BT2(NBANDS) = -1.0
C
 1000 CONTINUE
      IF(IOUT.EQ.0)  RETURN
      WRITE(6,1001) TIME,NBANDS
 1001 FORMAT(  1X,'TIME=',F9.3, ',GBS FINISHED WITH NBANDS = ',I5)
      IF(NBANDS.EQ.0)  RETURN
      DO 1002 J = 1,NBANDS
 1002 WRITE(6,1003)J,TBAND(J),VBAND(J),XTE(J),XLE(J),BT1(J),BT2(J)
 1003 FORMAT(1X,'BAND NO. ',I2,' ...',6F12.3)
      RETURN
      END
      SUBROUTINE XLTE(ZETA,ZLEN,ZLTHOY,VNOW,EDGE)
      COMMON/GBT/NBANDS,TBAND(15),VBAND(15),XLE(15),XTE(15),
     *             BT1(15),BT2(15),ALLG,VMRG
      COMMON/TIMER/ICLOCK,TIME,TNEXT
      DATA ACC/3.0/
C
C     ROUTINE TO SIMULATE BAND POSITIONING LOGIC FOR TAMPA VARIABLE
C     GREEN BAND SPEED CASE.
C
      UFTMP = ZETA + ZLTHOY + ZLEN - TIME
      WORK1 = (VMRG*VMRG - 1936.)/6.
      PAM = (580. - WORK1)/VMRG
      UFTAE = UFTMP - PAM
      UFTSL = UFTAE - ((VMRG-44.)/ACC)
      UFTDB = UFTSL - 6.
C
      IF(UFTMP.LT.0.)  GO TO 100
      IF(UFTAE.LT.0.)  GO TO 200
      IF(UFTSL.LT.0.)  GO TO 300
C
C     BAND EDGE IDENTIFIED AS BEING IN 30 MPH SECTION...
C     SIMULATION OF ON-LINE CODE AT LABEL SLOW...
      VNOW = 44.
      EDGE = -UFTDB * 44.
      RETURN
C
C     SIMULATION OF ON-LINE CODE AT LABEL ATMP...
  100 VNOW = VMRG
      EDGE = 844.
      RETURN
C
C     SIMULATION OF ON-LINE CODE AT LABEL FAST...
  200 VNOW = VMRG
      EDGE = 844. - (UFTMP*VMRG)
      RETURN
C
C     SIMULATION OF ON-LINE CODE AT LABEL UFACC...
  300 VNOW = 44. - (UFTSL*3.)
C     SET BAND 'STILL ACCELERATING' CONDITION...
      VNOW = - VNOW
      EDGE = 264. + (VNOW*VNOW - 1936.)/6.
      RETURN
      END
      SUBROUTINE RAYGAP(ITRAIL,ILEAD,RGAP)
      COMMON/FWYDAT/NVEH,FETA(63),FT1(63),FVEL(63),FXLEN(63),NC(63)
      COMMON/GBT/NBANDS,TBAND(15),VBAND(15),XLE(15),XTE(15),
     *           BT1(15),BT2(15),ALLG,VMRG
      DATA HZERO /0.8/
      DATA DEE /4.0/
      DATA TLRAMP/0.3/
C
C     RAYGAP IMPLEMENTS THE ALGORITHM USED BY RAYTHEON TO COMPUTE
C     THE REQUIRED GAP SIZE FOR GREEN BAND GENERATION AS A FUNCTION
C     OF THE VELOCITIES OF THE LEADING AND TRAILING FREEWAY VEHICLES
C     DEFINING A GAP, AND THE VELOCITY OF THE RAMP VEHICLE BEING
C     CONSIDERED FOR THE GAP.  SINCE THE GREEN BAND RAMP VEHICLES ARE
C     NOT TRACKED BY THE ON-LINE SYSTEM, THE CURRENT GREEN BAND SPEED
C     IS USED FOR THE RAMP VEHICLE SPEED.
C
C     RGAP = (H1+H1P+HZERO) + (H2+H2P+HZERO) + TLRAMP
C
      VT = FVEL(ITRAIL)
      VL = FVEL(ILEAD)
C
      IF(VT.GT.VL.AND.VMRG.GT.VL)  GO TO 100
      IF(VT.GT.VL.AND.VL.GT.VMRG)  GO TO 200
      IF(VL.GT.VT.AND.VT.GT.VMRG)  GO TO 300
      IF(VL.GT.VT.AND.VMRG.GT.VT.AND.VMRG.GT.VL)  GO TO 400
      IF(VL.GT.VT.AND.VMRG.GT.VT.AND.VL.GT.VMRG)  GO TO 500
      RGAP = 1.0E50
      RETURN
C
  100 H1 = (VMRG-VL)*(VMRG-VL)/(2.0*DEE*VL)
      H2 = (VT-VL)*(VT-VL)/(2.0*DEE*VL)
      GO TO 600
C
  200 H1 = 0.
```

```
      H2 = ((VT-VL)*(VT-VL)/(2.0*DEE*VL)) + F2(VMRG,VL)
      GO TO 600
C
  300 H1 = 0.
      H2 = F2(VMRG,VT)
      GO TO 600
C
  400 H1 = (VMRG-VL)*(VMRG-VL)/(2.0*DEE*VL)
      H2 = 0.
      GO TO 600
C
  500 H1 = 0.
      H2 = 0.
      GO TO 600
C
C     COMPUTE ETA PREDICTION ERROR ALLOWANCE...
  600 H1P = 0.777*F3(VL)*(FETA(ILEAD)-FT1(ILEAD))
      H2P = 0.777*F3(VT)*(FETA(ITRAIL)-FT1(ITRAIL))
C
      RGAP = H1 + H1P + H2 + H2P + 2.0*HZERO + TLRAMP
      RETURN
      END
      FUNCTION F2(V1,V2)
C
C     THIS FUNCTION COMPUTES THE TIME TO ACCELERATE FROM V1 TO V2
C     IN SECONDS.  V1 AND V2 ARE TO BE SUPPLIED IN FT/SEC.
C
      VZERO = 146.7
      ALPHA = 5.
      VDIFF = V2 - V1
      TERM = (VZERO-V2)/(VZERO-V1)
      FTIME = (VZERO/(ALPHA*V2))
      FTIME = FTIME*(VDIFF+(VZERO-V2)*ALOG(TERM))
C
      ATIME = 0.11*VDIFF - 0.925
      IF(VDIFF.LE.17.5)  ATIME = 0.057*VDIFF
      IF(VDIFF.GE.41.)  ATIME = 0.16*VDIFF - 2.85
C
C     IF THE 'TRUE' FORMULA FOR F2 IS TO BE USED, SET F2 EQUAL TO
C     THE VARIABLE FTIME IN TTHE FOLLOWING ASSIGNMENT.
C
      F2 = ATIME
      RETURN
      END
      FUNCTION F3(VEL)
C
C     F3(VEL) COMPUTES A TERM IN THE EQUATION USED BY RAYTHEON
C     TO PREDICT FWY VEHICLE ETA UNCERTAINTY IN THE REQUIRED GAP
C     CALCULATIONS.
C
C     VEL IS SUPPLIED IN UNITS OF FT/SEC
C
      F3 = 0.01 + ((88.-VEL)/73.5)
C
      IF(VEL.LT.14.7)  F3 = 0.10
C
      IF(VEL.GT.88.0)  F3 = 0.01
C
      RETURN
      END
      SUBROUTINE GBUD
      COMMON/GBT/NBANDS,TBAND(15),VBAND(15),XLE(15),XTE(15),
     *            BT1(15),BT2(15),ALLG,VMRG
      COMMON/TIMER/ICLOCK,TIME,TNEXT
      INTEGER*2 FIELD(80),GEE,IBLANK
      REAL*4 ACCEL /3.0/
      DATA GEE,IBLANK /'G', ' '/
      DATA DT /0.010/
C
C     THIS ROUTINE SIMULATES THE GBUD ROUTINE IN THE ON-LINE SYSTEM.
C     DATA IN THE CURRENT GREEN BAND TABLE IS UPDATED AND DISPLAYED
C     ON THE SIMULATED FIELD LIGHTS.
C
      IF(ALLG.LT.1)  GO TO 100
      DO 50 I = 1,80
   50 FIELD(I) = GEE
      GO TO 1000
C
C     CLEAR BAND DISPLAY FOR NEW DATA...
  100 DO 101 I = 1,80
  101 FIELD(I) = IBLANK
C
C     SCAN BAND TABLE
      IF(NBANDS.EQ.0)  GO TO 1000
      DO 105 K = 1,NBANDS
C     DO NOT PROCESS BAND IF XTE IS FARTHER ALONG DISPLAY THAN XLE...
      IF(XTE(K).GE.XLE(K))  GO TO 105
C
C     CONSTANT VELOCITY BAND
      IF(VBAND(K).GT.0.)  GO TO 150
C
C     NO, STILL ACCELERATING...
      VB = ABS(VBAND(K)) + ACCEL*DT
      IF(VB.GE.VMRG)  VBAND(K) = VMRG
      IF(VB.LT.VMRG)  VBAND(K) = -VB
C
C     UPDATE LEADING AND TRAILING EDGES OF BAND...
  150 DX = VB * DT
      XTE(K) = XTE(K) + DX
      XLE(K) = XLE(K) + DX
C
      IGO = XTE(K)/8.
      ISTOP = XLE(K)/8.
C
      IF(IGO.GT.80)  GO TO 105
      IF(ISTOP.LE.0)  GO TO 105
      IF(ISTOP.GT.80)  ISTOP = 80
      IF(IGO.LE.0)  IGO = 1
      IF(IGO.GE.ISTOP)  GO TO 105
C
      DO 160 I = IGO,ISTOP
  160 FIELD(I) = GEE
  105 CONTINUE
C
C     OUTPUT BAND DISPLAY JUST CREATED TO FIELD...
 1000 WRITE(8,1001)  TIME,FIELD
 1001 FORMAT(1X,F10.3,5X,80A1)
      RETURN
      END
```

LIST OF REFERENCES

1. Wattleworth, J. A., Peak Period Control of a Freeway System--Some Theoretical Considerations, Doctoral Dissertation, Northwestern University, Chicago, 1963.

2. Drew, D. R., A Study of Freeway Traffic Congestion, Doctoral Dissertation, Texas A & M University, College Station, Texas, 1964.

3. May, A. D., "Experimentation with Manual and Automatic Ramp Control," Highway Research Record No. 59, Highway Research Board, Washington, D. C., 1964.

4. Gervais, E. F., "Optimization of Freeway Traffic by Ramp Control," Highway Research Record No. 59, Highway Research Board, Washington, D. C., 1964.

5. Drew, D. R., Carvell, J. D., and Keese, C. J., "Freeway Surveillance and Control Research in Houston and Detroit," Paper presented to the Committee on Electronics, American Association of State Highway Officials, Salt Lake City, Utah, October, 1967.

6. Drew, D. R., "Stochastic Considerations in Freeway Operations and Control," Research Report No. 24-5, Texas Transportation Institute, Texas A & M University, College Station, Texas, 1965.

7. Wattleworth, J. A., Buhr, J. H., Drew, D. R., and Gerig, F. A., "Operational Effects of Some Entrance Ramp Geometrics on Freeway Merging," Highway Research Record No. 208, Highway Research Board, Washington, D. C., 1967.

8. Buhr, J. H., Drew, D. R., Wattleworth, J. A., and William, T. G., "A Nationwide Study of Freeway Merging Operations," Report 430-1, Texas Transportation Institute, Texas A & M University, College Station, Texas, 1967.

9. Wattleworth, J. A., Buhr, J. H., Drew, D. R., and Gerig, F. A., "Operational Effects of Some Entrance Ramp Geometrics on Freeway Merging," Report 430-3, Texas Transportation Institute, Texas A & M University, College Station, Texas, 1967.

10. Drew, D. R., Buhr, J. H., and Whitson, R. H., "The Determination of Merging Capacity and Its Application to Freeway Design and Control," Report 430-4, Texas Transportation Institute, Texas A & M University, College Station, Texas, 1967.

11. Wattleworth, J. A., Wallace, C. E., and Levin, Moshe, "Development and Evaluation of a Ramp Metering System on the Lodge Freeway," Research Report 488-3, Texas Transportation Institute, Texas A & M University, College Station, Texas, 1967.

12. Drew, D. R., LaMotte, L. R., Wattleworth, J. A., and Buhr, J. H., "Gap Acceptance in the Freeway Merging Process," Highway Research Record No. 208, Highway Research Board, Washington, D. C., 1967.

13. Buhr, J. H., Whitson, R. H., Brewer, K. A., and Drew, D. R., "Traffic Characteristics for Implementation and Calibration of Freeway Merging Control Systems," Highway Research Record No. 279, Highway Research Board, Washington, D. C., 1969.

14. Brewer, K. A., Buhr, J. H., Drew, D. R., and Messer, C. J., "Ramp Capacity and Service Volume as Related to Freeway Control," Highway Research Record No. 279, Highway Research Board, Washington, D. C., 1969.

15. Drew, D. R., Brewer, K. A., Buhr, J. H., and Whitson, R. H., "Multilevel Approach to the Design of a Freeway Control System," Highway Research Record No. 279, Highway Research Board, Washington, D. C., 1969.

16. Buhr, J. H., Radke, M. L., Kirk, B. M., and Drew, D. R., "A Moving Vehicle Merge Control System," Highway Research Record No. 279, Highway Research Board, Washington, D. C., 1969.

17. Gap Acceptance and Traffic Interaction in the Freeway Merging Process--Phase II, Final Report on Contract CPR-11-5284, Texas A & M University, College Station, Texas, 1970.

18. Development and Evaluation of Second Generation Analog Merging Controllers, A Supplement to the Final Project Report Gap Acceptance and Traffic Interaction in the Freeway Merging Process--Phase II, Texas Transporation Institute, Texas A & M University, College Station, Texas, 1970.

19. Dawson, R. F., and Michael, H. L., "Analysis of On Ramp Capacities by Monte-Carlo Simulation," Highway Research

Record No. 118, Highway Research Board, Washington, D. C., 1966.

20. Worrall, R. D., Coutts, D. W., Echterhoff-Hammerschmid, H., and Berry, D. S., "Merging Behavior at Freeway Entrance Ramps: Some Elementary Empirical Considerations," Highway Research Record No. 157, Highway Research Board, Washington, D. C., 1967.

21. McDermott, J. M., "Operational Effects of Automatic Ramp Control on Network Traffic," Highway Research Record No. 202, Highway Research, Washington, D. C., 1967.

22. Weiner, R. S., Some Theoretical Considerations in the Design of Gap Acceptance Ramp Control Systems for Urban Freeways, Doctoral Dissertation, Polytechnic Institute of Brooklyn, New York, 1968.

23. Buhr, J. H., McCasland, W. R., Carvell, J. D., and Drew, D. R., "Design of Freeway Entrance Ramp Merging Control Systems," Highway Research Record No. 279, Highway Research Board, Washington, D. C., 1969.

24. Newman, L., Dunnet, A. M., and Meis, G. J., "Freeway Ramp Control--What It Can and Cannot Do," Traffic Engineering, Vol. 19, No. 7, June, 1969.

25. Yagoda, H. N., and Pignataro, L. J., "The Analysis and Design of Freeway Entrance Ramp Control Systems," Highway Research Record No. 303, Highway Research Board, Washington, D. C., 1970.

26. Brewer, K. A., "Analysis of a Signal-Controlled Ramp's Characteristics," Highway Research Record No. 308, Highway Research Board, Washington, D. C., 1970.

27. Cooper, D. L., and Walinchus, R. J., "Measure of Effectiveness for Urban Traffic Control Systems," Highway Research Record No. 321, Highway Research Board, Washington, D. C., 1970.

28. West, J. T., "California Makes Its Move," Traffic Engineering, Vol. 41, No. 4, January, 1971, pp. 12-18.

29. Dudek, C. L., and McCasland, W. R., "Cost Effectiveness of Freeway Merging Control," Highway Research Record No. 363, Highway Research Board, Washington, D. C., 1971.

30. Shaw, L., "On Optimal Ramp Control of Traffic Jam Queues," IEEE Transactions on Automatic Controls, Vol. AC-17, No. 5, October, 1972, pp. 630-637.

31. Payne, H. J., Meisel, W. S., and Teener, M. D., "Ramp Control to Relieve Freeway Congestion Caused by Traffic Disturbances," Highway Research Record No. 469, Highway Research Board, Washington, D. C., 1973.

32. Wang, J. J., and May, A. D., "Computer Model for Optimal Freeway On-Ramp Control," Highway Research Record No. 469, Highway Research Board, Washington, D. C., 1973.

33. Klee, H. I., "An Algorithm for Synchronizing Entrance Ramp Vehicles and Freeway Gaps," ASME Transactions, Journal of Dynamic Systems, Measurement, and Control, June, 1973, pp. 204-212.

34. Chandler, R. E., Herman, R., and Montroll, E. W., "Traffic Dynamics Studies in Car Following," Operations Research, Vol. 6, 1958, pp. 165-184.

35. Herman, R., Montroll, E. W., Potts, R. B., and Rotherey, R. W., "Traffic Dynamics: Analysis of Stability in Car Following," Operations Research, Vol. 7, 1959, pp. 86-106.

36. Gazis, D. C., Herman, R., and Potts, R. B., "Car-Following Theory of Steady-State Traffic Flow," Operations Research, Vol. 7, 1959, pp. 499-505.

37. Gazis, D. C., Herman, R., and Weiss, G. H., "Density Oscillations Between Lanes of a Multilane Highway," Operations Research, Vol. 10, 1962, pp. 658-667.

38. Jones, T. R., and Potts, R. B., "The Measurement of Acceleration Noise--A Traffic Parameter," Operations Research, Vol. 10, 1962, pp. 745-763.

39. Haight, F. A., Mathematical Theories of Traffic Flow, New York: Academic Press, 1963.

40. Gerlough, D. L., and Capelle, D. G., "An Introduction to Traffic Flow Theory," Special Report 79, Highway Research Board, Washington, D. C., 1964.

41. Ashton, W. D., The Theory of Road Traffic Flow, New York: John Wiley & Sons, 1966.

42. May, A. D., and Keller, H. E. M., "Non-Integer Car Following Models," Highway Research Record No. 199, Highway Research Board, Washington, D. C., 1967.

43. Fox, P., and Lehman, F. G., "A Digital Simulation of Car Following and Overtaking," Highway Research Record No. 199, Highway Research Board, Washington, D. C., 1967.

44. Drew, D. R., Traffic Flow Theory and Control, New York: McGraw-Hill, 1968.

45. Mika, H. S., Kreer, J. B., and Yuan, L. S., "Dual Mode Behavior of Freeway Traffic," Highway Research Record No. 279, Highway Research Board, Washington, D. C., 1969.

46. Bullen, A. G. R., and Worrall, R. D., "Formulating a Model of Multilane Traffic Flow," Highway Research Record No. 334, Highway Research Board, Washington, D. C., 1970.

47. Stochastic Modelling of the Freeway Merging Process, Division of Transportation Planning Report, Polytechnic Institute of Brooklyn, N. Y., 1970.

48. Foote, R. S., "Instrumentation Development and Contributions from Traffic Flow Theory," Highway Research Record No. 368, Highway Research Board, Washington, D. C., 1971.

49. Gafarian, A. V., Lawrence, R. L., Munjal, P. K., Pahl, J., "On Experimental Validation of Various Methods for Obtaining Relationships Between Traffic Flow, Concentration, and Speed on Multilane Highways," Highway Research Record No. 349, Highway Research Board, Washington, D. C., 1971.

50. Prigogine, I., and Herman, R., Kinetic Theory of Vehicular Traffic, New York: American Elsevier, 1971.

51. Munjal, P. K., Hsu, Y. S., and Carpenter, R., "Experimental Validation of Modified Boltzmann Type of Model and Shift Model for Multilane Traffic Flow," Highway Research Record No. 409, Highway Research Board, Washington, D. C., 1972.

52. Pahl, J., "Lane-Change Frequencies in Traffic Flow," Highway Research Record No. 409, Highway Research Board, Washington, D. C., 1972.

53. Lee, J., and Yu, J. C., "Internal Energy of Traffic Flows," Highway Research Record No. 456, Highway Research Board, Washington, D. C., 1973.

54. Munjal, P. K., and Hsu, Y. S., "Characteristics of Freeway Traffic and of Freeway-Lane Changing Behavior," Highway Research Record No. 453, Highway Research Board, Washington, D. C., 1973.

55. Dudek, C. L., and Messer, C. J., "Detecting Stoppage Waves for Freeway Control," Highway Research Record No. 469, Highway Research Board, Washington, D. C., 1973.

56. Oliver, R. M., "Distribution of Gaps and Blocks in a Traffic Stream," Operations Research, Vol. 10, 1962, pp. 197-217.

57. Solberg, P., and Oppenlander, J. C., "Lag and Gap Acceptance at Stop-Controlled Intersections," Highway Research Record No. 118, Highway Research Board, Washington, D. C., 1966.

58. Drew, D. R., "Gap Acceptance Characteristics for Ramp-Freeway Surveillance and Control," Highway Research Record No. 157, Highway Research Board, Washington, D. C., 1967.

59. Miller, A. J., "Nine Estimators of Gap Acceptance Parameters," Proceedings of the Fifth International Symposium on the Theory of Traffic Flow and Transportation, Newell, G. F., ed., New York: American Elsevier, 1971.

60. Pahl, J., "Gap Acceptance Characteristics in Freeway Traffic Flow," Highway Research Record No. 409, Highway Research Board, Washington, D. C., 1972.

61. Buhr, J. H., "Gap Stability and Its Application to Freeway Merging Control Systems," Traffic Engineering, March, 1968, pp. 36-53.

62. Munjal, P. K., Hsu, Y. S., and Lawrence, R. L., "Prediction and Stability of Freeway Gaps and On-Ramp Merging," Highway Research Record No. 469, Highway Research Board, Washington, D. C., 1973.

63. Evans, D. H., Herman, R., and Weiss, G. H., "The Highway Merging and Queueing Problem," Operations Research, Vol. 12, 1964, pp. 832-857.

64. Jewell, W. S., "Forced Merging in Traffic," Operations Research, Vol. 12, 1964, pp. 858-869.

65. Marcus, A., "Theoretical Analysis of Expressway Ramp Merge Controls as Single-Server and Tandem Queues," Proceedings of the Fifth International Symposium on the Theory of Traffic Flow and Transportation, Newell, G. F., ed., New York: American Elsevier, 1971.

66. Stern, S., "Traffic Flow Data Acquisition Using Magnetic Loop Vehicle Detectors," Highway Research Record No. 154, Highway Research Board, Washington, D. C., 1967.

67. Christensen, A., "Use of a Computer and Vehicle Length Detectors to Measure Queues and Delays at Signalized In-

tersections," Highway Research Record No. 211, Highway Research Board, Washington, D. C., 1967.

68. "Vehicle Detector Tests," Advanced Control Technology in Urban Traffic Control Systems, Vol. 4, Sperry Systems Management Division, Sperry Rand Corporation, Great Neck, New York, 1969.

69. Courage, K. G., "Some Electronic Measurements of Macroscopic Traffic Characteristics on a Multilane Freeway," Highway Research Record No. 279, Highway Research Board, Washington, D. c., 1969.

70. Gazis, D. C., and Foote, R. S., "Calibration and Correction of Magnetic Loop Detectors," Highway Research Record No. 325, Highway Research Board, Washington, D. C., 1970.

71. Gordon, R. L., Dodge, K. W., and Scott, J. E., "Surveillance Aspects of a Computer Controlled Traffic System," IEEE Transactions on Vehicular Technology, Vol. VT-19, No. 1, February, 1970, pp. 90-97.

72. Pahl, J., "The Effect of Discrete Time Measurement on Speed Data," Highway Research Record No. 349, Highway Research Board, Washington, D. C., 1971.

73. Huckins, H. C., "Notes on the Error Possibilities in Velocity Measurement Utilizing Vehicle Detector Loop Pairs," unpublished working paper, Office of Development, Federal Highway Administration, Washington, D. C., 1972.

74. Mikhalkin, B. C., Payne, H. J., and Isaksen, L., "Estimation of Speed from Presence Detectors," Highway Research Record No. 388, Highway Research Board, Washington, D. C., 1972.

75. Bushnell, D., "A Merging Control System for the Urban Freeway," IEEE Transactions on Vehicular Technology, Vol. VT-19, No. 1, February, 1970, pp. 107-119.

76. Pacer System Analysis and Design, Vol. I, Merging Control System Final Report, Report No. ER70-4200, Equipment Division, Raytheon Company, Sudbury, Massachusetts, October, 1970.

77. Pacer System Software, Vol. II, Merging Control System Final Report, Report No. ER70-4200, Equipment Division, Raytheon Company, Sudbury Massachusetts, October 1970.

78. Pacer System Program Listing, Vol. III, Merging Control System Final Report, Report No. ER70-4200, Equipment Division, Raytheon Company, Sudbury, Massachusetts, October, 1970.

79. Pacer System Performance Data, Vol. IV, Merging Control System Final Report, Report No. ER70-4200, Equipment Division, Raytheon Company, Sudbury, Massachusetts, October, 1970.

80. Pacer System Performance Evaluation, Vol. V, Merging Control System Final Report, Report No. ER70-4200, Equipment Division, Raytheon Company, Sudbury, Massachusetts, October, 1970.

81. Preliminary Studies, Vol. VI, Merging Control System Final Report, Report No. ER70-4200, Equipment Division, Raytheon Company, Sudbury, Massachusetts, October, 1970.

82. Adaptive System Analysis and Specifications, Vol. VII, Merging Control System Final Report, Report No. ER70-4200, Equipment Division, Raytheon Company, Sudbury, Massachusetts, October, 1970.

83. Green Band Design, Vol. VIII, Merging Control System Final Report, Report No. ER70-4200, Equipment Division, Raytheon Company, Sudbury, Massachusetts, October, 1970.

84. Green Band Performance Data, Vol. IX, Merging Control System Final Report, Report No. ER70-4200, Equipment Division, Raytheon Company, Sudbury, Massachusetts, October, 1970.

85. Green Band Performance Evaluation, Vol. X, Merging Control System Final Report, Report No. ER70-4200, Equipment Division, Raytheon Company, Sudbury, Massachusetts, October, 1970.

86. Merging Control Systems, Office of Research and Development, Federal Highway Administration, Washington, D. C., May, 1971.

87. True, J., and Rosen, D., "Moving Merge--A New Concept in Ramp Control," Public Roads, Vol. 37, No. 7, December, 1973, pp. 229-245.

88. Tignor, S. C., Operational Analyses and Improvements for Freeway Moving-Merge Systems, Doctoral Dissertation, University of Michigan, 1974.

89. Highway Capacity Manual, Special Report 87, Highway Research Board, Washington, D. C., 1965.

90. Raytheon 704 Computer User's Manual, Raytheon Computer Company, Santa Ana, California, August, 1970.

91. *Raytheon Data Systems 704 Computer Price List*, Price List PL-704B, Raytheon Data Systems, Norwood, Massachusetts, 1972.

92. *Implementation and Evaluation of a Merging Control System in Tampa, Florida: First Interim Report*, Transportation Research Center, University of Florida, Gainesville, Florida, January, 1973.

93. *Implementation and Evaluation of a Merging Control System in Tampa, Florida: Second Interim Report*, Transportation Research Center, University of Florida, Gainesville, Florida, May, 1973.

94. *Implementation and Evaluation of a Merging Control System in Tampa, Florida: Third Interim Report*, Transportation Research Center, University of Florida, Gainesville, Florida, July, 1973.

95. *Implementation and Evaluation of a Merging Control System in Tampa, Florida: Fourth Interim Report*, Transportation Research Center, University of Florida, Gainesville, Florida, March, 1974.

96. *Manual on Uniform Traffic Control Devices*, Federal Highway Administration, U. S. Department of Transportation, 1971.

97. *8008 Central Processing Unit User's Manual*, Intel Corporation, Santa Clara, California, November, 1973.

98. Yasaki, E. K., "The Emerging Microcomputer," *Datamation*, December, 1974, pp. 81-86.

99. Theis, D. J., "Microprocessor and Microcomputer Survey," *Datamation*, December, 1974, pp. 90-101.

100. Weissberger, A. J., "MOS/LSI Microprocessor Selection," *Electronic Design 12*, June 7, 1974, pp. 100-104.

101. Altman, L., "Single Chip Microprocessors Open Up a New World of Applications," *Electronics*, April 18, 1974, pp. 81-87.

102. Young L., Bennett, T., and Lavell, J., "N Channel MOS Technology Yields New Generation of Microprocessors," *Electronics*, April 18, 1974, pp. 88-95.

103. Shima, M., and Faggin, F., "In Switch to N-MOS, Microprocessor Gets a 2-US Cycle Time," *Electronics*, April 18, 1974, pp. 95-100.

104. Weiss, C. D., "Basic Microcomputer Software," Electronic Design 9, April 26, 1974, pp. 142-146.

105. The Value of Micropower...A Microcomputer Handbook, General Automation, Inc., Anaheim, California, 1974.

106. Raytheon Bipolar LSI 16 Bit Microprocessor Set, Advanced Product Description RP-16, Raytheon Semiconductor Division, Mountain View, California, June, 1974.

107. A Guide to PL/M Programming, Intel Corporation, Santa Clara, California, September, 1973.

108. Radoy, C. H., Copeland, G. P., and Lipovski, G. J., "A Methodology for Parallel Processing Design Tradeoffs," Proceedings of the First Symposium on Computer Architecture, Institute of Electrical and Electronic Engineers, New York, December, 1973.

ADDITIONAL REFERENCES

Duff, J. T., "Accomplishments in Freeway Operations Outside the United States," Highway Research Record No. 368, Highway Research Board, Washington, D. C., 1971.

Wattleworth, J. A., "Accomplishments in Freeway Operations in the United States," Highway Research Record No. 368, Highway Research Board, Washington, D. C., 1971.

Measures of the Quality of Traffic Service, Special Report No. 130, Highway Research Board, Washington, D. C., 1972.

Everall, P. F., *Urban Freeway Surveillance and Control: The State of the Art*, Federal Highway Administration, Washington, D. C., 1972.

Stockfish, C. R., *Selecting Digital Computer Signal Systems*, Traffic Systems Division, Federal Highway Administration, Washington, D. C., 1972.

A Policy on Design of Urban Highways and Arterial Streets, American Association of State Highway and Transportation Engineers, Washington, D. C., 1973.

Gazis, D. C., ed., *Traffic Science*, New York: Wiley-Interscience, 1974.

Sage, A. P., *Optimum Systems Control*, Englewood Cliffs, New Jersey: Prentice-Hall, 1968.

Sage, A. P., and Melsa, J. L., *Estimation Theory with Applications to Communications and Control*, New York: McGraw-Hill, 1971.

De Neufville, R., and Stafford, J. H., *Systems Analysis for Engineers and Managers*, New York: McGraw-Hill, 1971.

BIOGRAPHICAL SKETCH

Christian S. Bauer, Jr. was born in Biloxi, Mississippi, in September, 1944. He was graduated from the Winter Park High School in Winter Park, Florida, in 1962, and began his college work at the University of Oklahoma in September, 1962. He subsequently transferred to the University of Florida in Gainesville, Florida, in September, 1963, where he received the degrees of Bachelor of Science in Industrial Engineering in June, 1966, and Master of Science in Engineering in December, 1967. The work for the latter degree was taken under the program option in Computer Science offered by the Department of Industrial and System Engineering at the University.

From 1968 to the Fall of 1970, Bauer was employed by the Martin-Marietta Corporation in Orlando, Florida, as an Engineer in its Advanced Programs Division. In September of 1970, he accepted a position as an Assistant Professor in the Department of Industrial Engineering and Management Systems at Florida Technological University in Orlando. He served in that position until the September of 1972, when he was granted a leave-of-absence to pursue full-time study towards the Ph.D. degree specializing in Traffic and Transportation Engineering on the Gainesville campus of the University of Florida. Since that time, Bauer has served as a Research Assistant and as a Research Associate in the Department of Civil Engineering, where his work assignments have been with the research programs of the Transportation Research Center.

Christian S. Bauer, Jr. is a Registered Professional Engineer in the State of Florida, and holds memberships in the following technical and professional organizations: The Highway Research Board, The Institute of Traffic Engineers, The Operations Research Society of America, The American Institute of Industrial Engineers, The Association for Computing Machinery, Simulation Councils, Inc., and The American Society for Engineering Education. He is a member of the Engineering Honorary Societies Alpha Pi Mu and Tau Beta Pi.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Kenneth G. Courage, Chairman
Assistant Professor of Engineering

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Joseph A. Wattleworth

Joseph A. Wattleworth
Professor of Engineering

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

James H. Schaub

James H. Schaub
Professor of Engineering

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Frank D. Vickers

Frank D. Vickers
Associate Professor of Engineering

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Ray L. Ott, Jr.

Ray L. Ott, Jr.
Associate Professor of Statistics

This dissertation was submitted to the Graduate Faculty of the College of Engineering and to the Graduate Council, and was accepted as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

March, 1975.

Wayne H. Chen

Dean, College of Engineering

Dean, Graduate School